Application of MEMS in Turbomachinery Environment

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Abstract

MEMS are regarded to be an enabling technology allowing the development of smart products by augmenting the computational ability of microelectronics with the perception and control capabilities of micro-sensors and micro-actuators. MEMS technology makes possible the integration of microelectronics with active perception and control functions, thereby, greatly expanding the design and application space.

Thus MEMS are expected to be an enabling technology for future smart engine concepts in the Aero-Engine industry. Nevertheless, in the present state there are restrictions in the application of these devices in the harsh engine environment, which have to be overcome in order to take advantage of MEMS.

The presented paper will give an overview about potential fields of application for MEMS in Aero-Engine applications. The main goal of the paper is to identify those applications which offer technological benefits which can not be achieved with common technology and – derived from this – to show the necessary steps in future development of MEMS. It also should trigger a discussion about the applicability of MEMS devices in harsh environment.

Contents

Introduction

Micro-Electro-Mechanical Systems (MEMS) are the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology. It is considered to enable the development of SMART oriented products by augmenting the computational ability of microelectronics with perception and control capabilities. Micro-sensors and micro-actuators therefore enable the integration of microelectronics with active perception and adaptive control functions.

In the Aero-Engine industry an effort is presently being made to develop so-called Intelligent or Smart Engines. The focus of these new generation engines should be the capability to comprehend their environment and operating conditions, and consequently adapt themselves either to reach optimal performance, or to improve their reliability by detecting and avoiding failures. Due to the complexity of the flow field in the engine, and due to the very demanding temperature and pressure conditions, classical actuators and sensors have a very limited range of applications here.

The MEMS technologies provide a new range of applications, which could considerably extend the capabilities of a jet engine with regards to control and monitoring.

The major fields of applications of MEMS in jet engines focus on two areas. On the one hand, it would lead to a systematic monitoring of the engine through a complex state-of-the-art sensor network. Due to the versatility of MEMS sensors and their very small size, all aspects of flow and mechanical properties in several parts of the engine could be monitored much more precisely than today. A monitoring of vibrations, harness, flow, temperatures and emissions is thereby foreseen. On the other hand, MEMS would provide new-generation actuators, offering cutting-edge methods to control and improve flow, emissions, or instabilities phenomena.

Altogether MEMS technologies could constitute one of the missing parts on the path leading to the Intelligent Engine, by means of both new-generation sensors and actuators.

1. Possible MEMS applications in aero-engines

1.1. Use of improved actuators to increase engine performance

In the last years many so-called “smart” applications were identified in order to increase engine performance by introducing more intelligent capabilities into the different components of the engine. The common idea to all these attempts is the extension of the physically limited operating range of engine components by using smart controls and advanced actuation. Affecting the operating conditions in this way may offer the possibility to increase the useable range and take advantage of this new degree of freedom in different ways. Some examples for such attempts are:

- *Active surge control*
  With focus on extension of the useable operating range of compressors to achieve improvements in efficiency and/or operability.
- *Active vibration control*
  Aiming at increased useable life of blades and vanes.
- *Active clearance control*
  Leading to increased efficiency and stability.
- *Boundary separation control*
  To avoid flow separation in different engine components such as engine intake, interducts or wings and blades.

Common to all these ideas is the need for very advanced devices to allow for defined and reliable actuation. Presently, only few actuators are available, which fulfil the demands on speed, accuracy, lifetime, reliability, cost and weight. In parallel to the efforts in improvement of actuators based on commonly available technologies, the focus on smart technologies such as MEMS, Smart Materials like SMA or piezo-structures has grown in the last years.

These technologies on the one hand offer a wide range of opportunities regarding flexibility, weight and costs, on the other hand strong restrictions in terms of lifetime and robustness in an engine environment are identified. Whereas for example pressure belts based on MEMS-Technology have been tested on aircraft wings, comparable applications in aero-engines have not been reported yet. The major restrictions for in-engine applications are the high temperatures, vibration levels and environmental conditions during operation, which will be discussed in a later section of this paper.

In order to define the requirements for MEMS application in engine environment more in detail, some features of a potential active surge control scheme shall be discussed in the following.

Active surge control
In the performance map of compressors the surge line is the limiting border towards low through-flow under steady state conditions. When the operating point crosses the surge line aerodynamic instabilities occur as either rotating stall or surge. They lead to a loss of performance of the compressor and increase the load on the blading as well as the whole gas turbine. To prevent the compressor from entering these unstable states, usually a safety margin must be observed in the performance map (Fig.1). Due to this margin the compressor cannot reach the regions of highest performance and efficiency and the whole engine suffers from restrictions in operability.

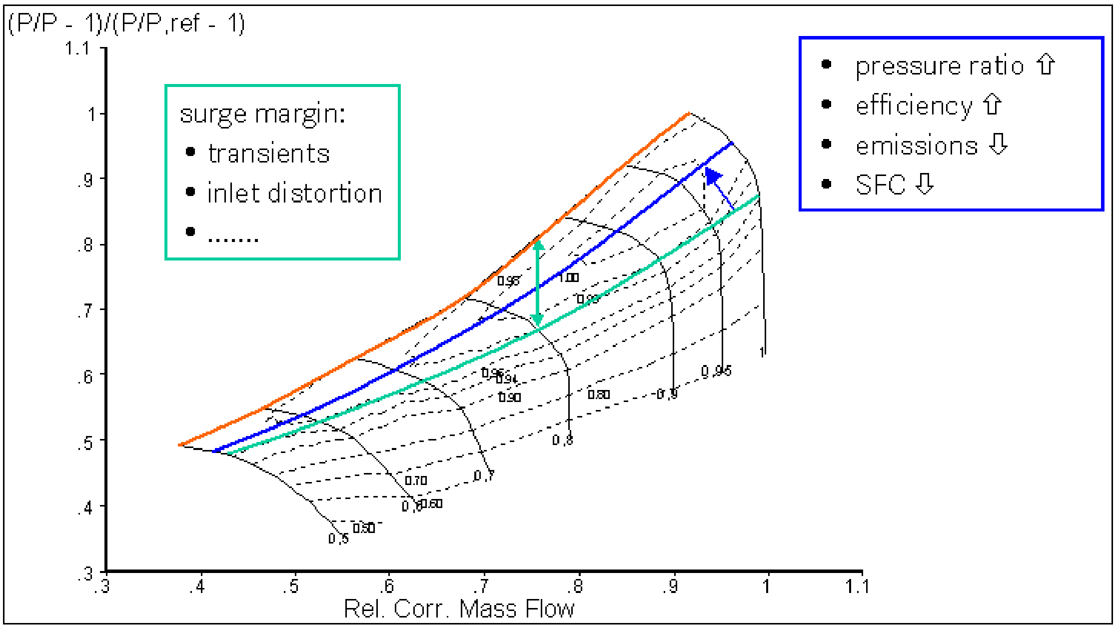

Fig.1: Compressor performance map with surge line (red), nominal operating line (green) and new operating line with reduced surge margin (blue).

The expression "active surge control" describes attempts to reduce the necessary surge margin in the design process and increase the available margin by active means whenever it is necessary during operation. This can be done by closed-loop control in combination with a preventive detection strategy or even scheduled in predefined operating ranges.

The increase in surge margin can be achieved by different control actions. One commonly investigated way of manipulating the surge line is the use of air injection into the compressor. Different lab scale demonstrators are described in the open literature [1, 2, 3, 4, 5, 6] using valves to control the injected air flow. All the described valves are rather heavy, big and expensive devices, which are far away from an application in an engine in service (see Fig.2 for example).

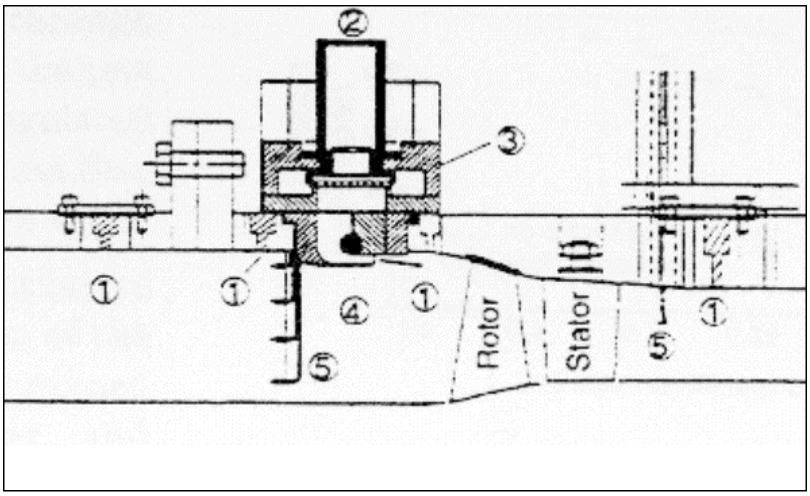

Fig. 2: Lab scale demo of air injection (Ref. [6]).

In the last years this conflict has lead to a deeper investigation of the possibilities to use smart devices like MEMS or Smart Materials as actuators for new control concepts. The challenge which manufacturers of these devices have to face is the harsh environment within engines combined with very high demands on reliability and robustness of the actuators.

When using MEMS technology for active surge control by air injection, the demands can be summarised as follows:

Modulation of valves	Full
Bandwidth	300 - 400 Hz
Injected mass flow	20 - 200 g/s
Temperature	up to 600 K
Properties	small, lightweight, robust, reliable, affordable

This example shows the difficulties in introducing such devices in an engine environment and gives a strong indication that some of the – successfully demonstrated – technologies (e.g. Si-based MEMS) will not be easily applicable for control purposes in gas turbines.

1.2. Use of improved sensors to monitor and improve engine health

The importance of monitoring in turbo-machinery cannot be over-stated. Though one production series brings similar engines under stringent tolerances, every single engine lives its own life depending on flight hours, mission profiles, environmental conditions etc.

Therefore, monitoring of engine states during flight is essential for keeping the safety and reliability. Additionally, more sensors for monitoring allow detection of impacts and consequent repair on-demand, and the amount of regular checks may thus decrease, which would consequently lead to a decrease in life cycle costs (LCC).
Nevertheless, new sensors should not increase the weight of the engine considerably. This makes MEMS devices attractive for flight applications where every additional weight counts.

These sensors also should survive in a harsh environment, which is discussed in the next chapter. "Smart" MEMS arrays may be attractive, if the elements of these arrays can detect their damaged "neighbours" and eliminate these from the aggregate measured value sent to the processing electronics.

Further we discuss potential applications of MEMS for monitoring in jet engines.

- *MEMS pressure sensors*

Distributed pressure sensors, e.g. pressure sensor "belts", could be put at the engine inlet for measurement of pressure distribution and detection of inlet pressure instabilities. Such instabilities arise generally during manoeuvres and high angles of attack when the air stream enters the engine in-homogeneously. The consequence is the decrease of the available surge margin. Present solution against these undetected instabilities is a stack-up in a surge margin design, which leads to too conservative operation during stable and homogenous inlet conditions.
Dynamic pressure sensing in front of or between compressor stages can detect rotating stalls and allow early surge detection. Present dynamic sensors are used during compressor testing but are not found installed on the engine due to their low robustness and short life.
The sensing in the gas path downstream from compressors might be too difficult because of high temperatures. Presently, temperatures at the high-pressure compressor outlet are up to 650°C and may be even higher in the future.

- *Leakages*

Detection of leakages reduces the danger of engine fire and increases the availability of aircraft through early repair.
Fuel and oil leakage could be detected by means of a capacitive co-axial “cables” that change their electrical capacity when fluid drops fall on them. A MEMS gas sensor could detect already evaporated kerosene.
Leakages of combustion gases can also be detected by temperature monitoring in the combustor casing.
Leakages in customer bleeds might lower the system efficiency. These leakages can be detected by temperature sensors in compressor area at their bleed valves.

- *Gas analysis - emissions*

Through the gas analysis the combustor deterioration can be detected: the rise of CHx compounds shows exactly the state of combustion.
Also, measurements of NOx would be a foundation for new control concepts for less pollutant combustors. This also gains importance in sense of new environmental-friendly engine developments.
There are well functioning gas analysis systems for industrial plants and automobiles, however, the authors are not aware of any airworthy gas analysis system.

- *Harness monitoring*

Harness monitoring receives also more and more attention, and it is not only the engine problem – kilometres of arteries network whole aircraft. With more long-lived aircraft in the future the aged harness will become more prominent. Isolation checks are already becoming a part of the maintenance checks; however, incidence failures, e.g. caused by lightning, cannot be detected on ground.
New methods may use the (frequency domain) reflectometry, sending a wave and analysing the state of harness with the shape of reflected signals (short circuits, breakages, corrosion and impedance changes). This could be realised as an intermediate device between accessories and their sensing/driving units.

Figure below shows expected positions of mentioned sensors:

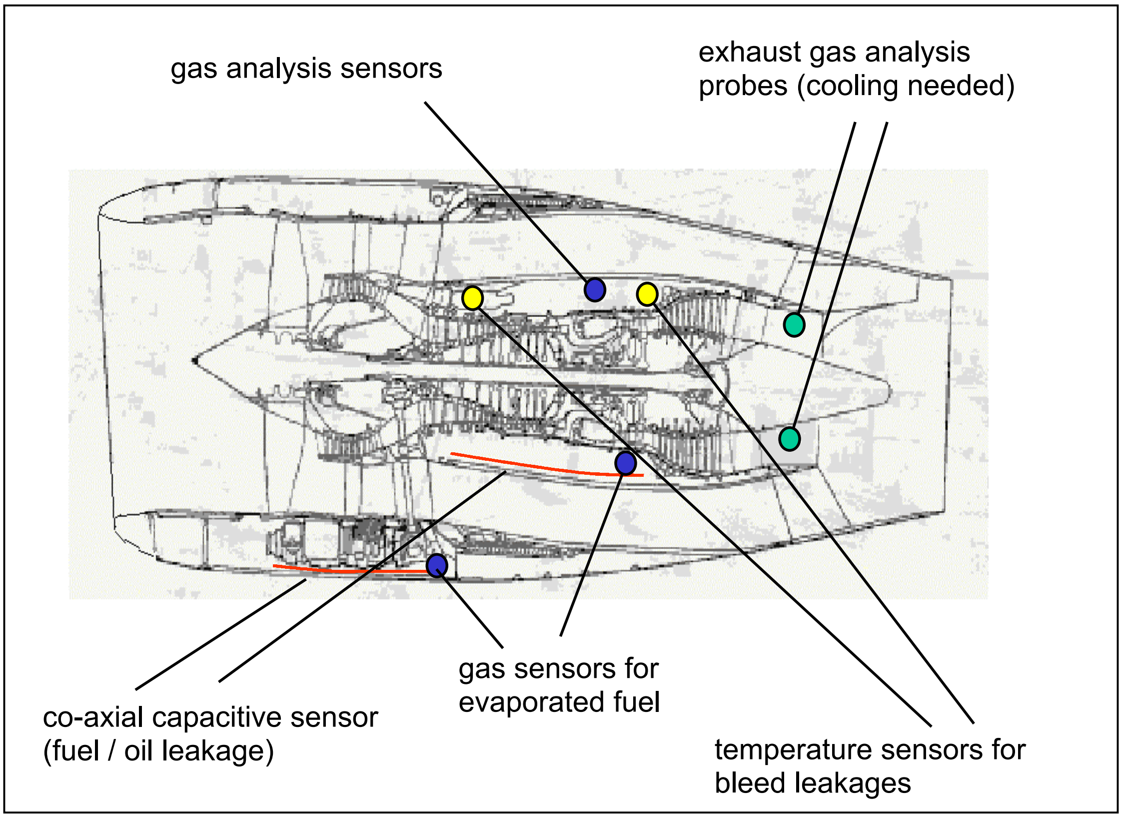

Fig. 3: Expected positions of MEMS based sensors in Aero-Engines.

2. Operating conditions of a jet engine

2.1. Fields of pressures and temperatures in the engine

The physical and chemical conditions occurring within the various parts of a turbine engine for a flying vehicle are probably among the harshest environments one can imagine for electronic devices of any kind. Dependent on the intended target location there will always be certain parameters describing the environment that require unique and possibly currently not yet available capabilities of materials used for micro-electronic circuitry to enable reliable long-term operation of such a device in this environment.

The most obvious parameters to describe the physical conditions within a turbine engine are the temperatures, pressures and velocities of the air in the primary gas path, which can be derived from the external conditions (outside air temperature, altitude, flight velocity) and from the well known laws governing the thermodynamic cycle describing the energy conversion process within the engine.

The design of existing engines typically exploits the mechanical and thermal capabilities of the strongest available metallic materials like Titanium or Nickel base alloys up to the limits of fracture toughness and life potential.

Typical conditions found in the gas path of a state-of-the art after-burning fighter engine are:

Typical temperatures in main engine sections (in °C)	
Inlet	-50 to 150 (*)
LP compressor exit	200
HP compressor exit	650
HPT inlet	1600
LPT exit	900
Nozzle with A/B operating	1850

(: consider also hot gas ingestion caused by re-circulation or exhaust plumes of other A/C)*

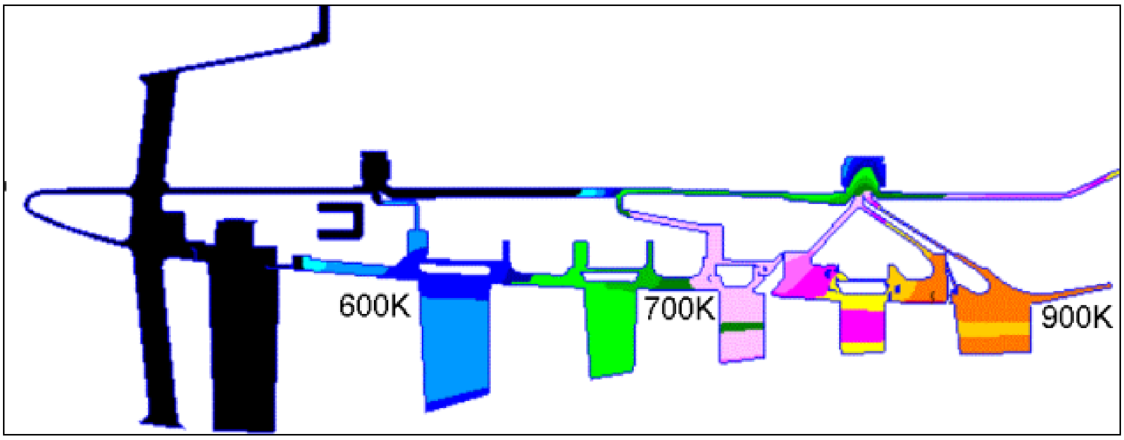

Fig. 4: Metal temperatures in HP compressor stator

Typical pressures in main engine sections (in kPa)	
Inlet	10...170
LP compressor exit	50...500
HP compressor exit	400...4000

During a surge event a device mounted in the inlet section may see considerably higher transient temperatures and pressures caused by the reverse flow of hot gas from the turbine section.

Although the intended application is to avoid such events by active counteraction, sensors and actuators in the engine inlet section have to survive such transient events without loosing their functionality. Worst case conditions might be up to 500 kPa and temperatures up to 950 °C for some ms.

The transient air temperatures induce corresponding transient thermal distributions within the static and rotating parts of the engine. Together with the mechanical loads from rotation, reaction forces, gas pressures etc. the temperature distributions give rise to complex stress fields potentially also influencing the candidate locations for MEMS devices. The integration of MEMS devices into the engine structure would have to take into account both the weakening of the engine components by the holes, grooves, cavities etc. needed to house the devices and the interaction with the deformations the structure experiences under operational loads.

Fig.5 shows an example of the metal temperature at a certain location of a compressor rotor for a military training flight.

Extreme cases for thermal cycling may occur during in-flight shutdown, where rotors and casings are cooled down to ambient conditions within very short times.

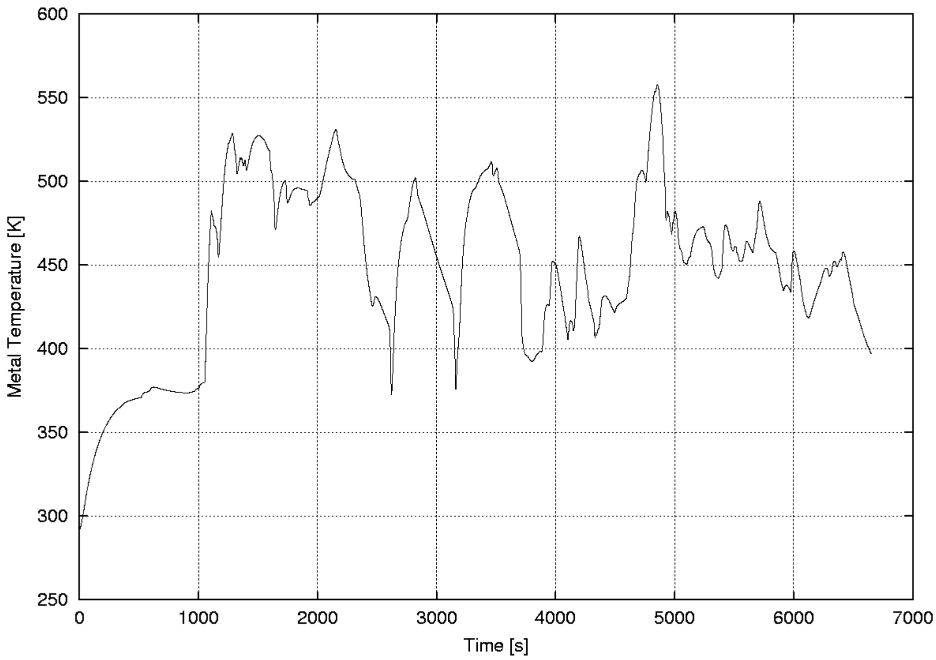

Fig. 5: Transient metal temperatures in a compressor rotor

2.2. Energy flows

Even if only very small percentages of the energy converted within the modules of the engine give rise to non-stationary air-flow and corresponding excitation of mechanical vibration, the available absolute amount of energy looks rather threatening to the survival of delicate electronic components in this environment (Fig.6).

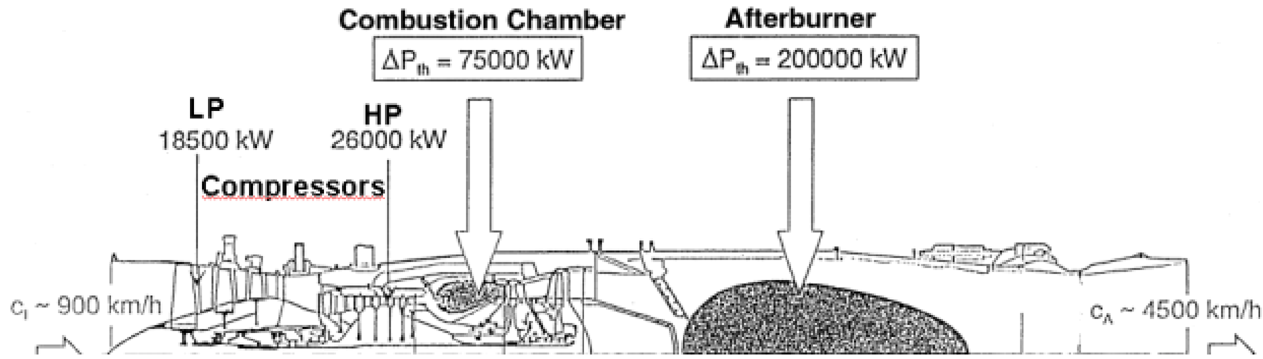

Fig. 6: Typical energy flows in an aero-engine at Ma =0,9, SL

3. Environment

3.1. Vibration exposure

The location of transducers and actuators in conventional designs is usually very carefully checked for an installation location that guarantees some protection against destruction or degradation by high vibration levels. With arrays of sensors and actuators it will not be possible to avoid certain locations with increased or even very high amplitudes.

Comprehensive testing will be necessary to prove the reliability of future MEMS installations. In the required airworthiness tests a combination of maximum vibration level and maximum limiting temperature has to be assumed. Vibration and stress measurements should be made at conditions of maximum inlet distortion, stall, limits of variable geometry travel if applicable, maximum compressor air bleed and power extraction, maximum inlet pressure and temperature capabilities of the engine and combinations thereof.

General guidance on vibration testing with some minimum requirements can be found in [7], resulting in test conditions as shown in Fig. 7. The exposure to vibration in a real engine is known to be rather complex, dependent on operating conditions and with considerable variations between individual engines. Experience from the development phase of current projects, like the Eurofighter engine EJ200 [8] will have to be used to tailor the testing methods for future advanced instrumentation and actuators.

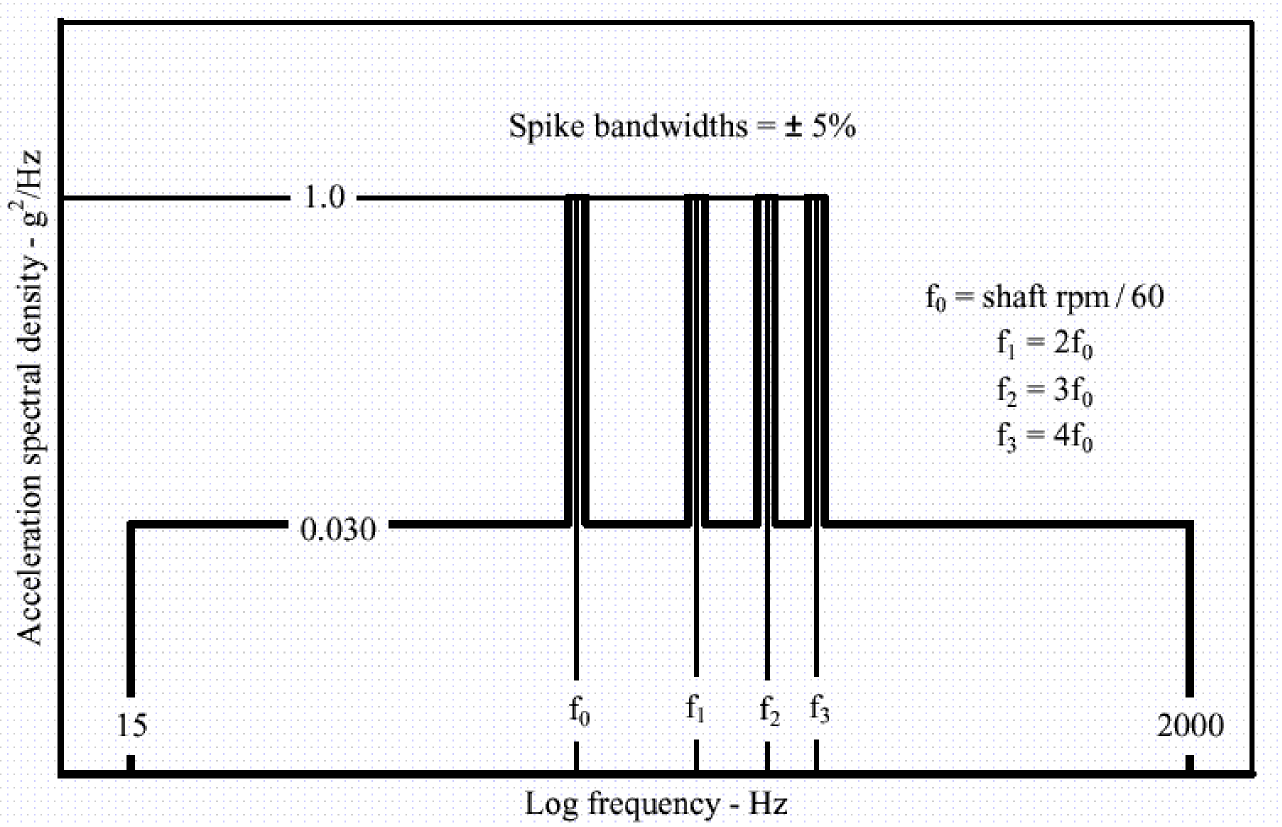

Fig. 7: Turbine engine vibration exposure, typical test conditions [7]

3.2. *Influence of external aggression factors*

Even a quick look at the "Laboratory test methods" sections of [MIL810] reveals some tough and sometimes rather discouraging aspects about the survivability of any device within the environment of a turbine engine. The list consists of the following items:

Laboratory test methods	
500.4	Low Pressure (Altitude)
501.4	High Temperature
502.4	Low Temperature
503.4	Temperature Shock
504	Contamination by Fluids
505.4	Solar Radiation (Sunshine)
506.4	Rain
507.4	Humidity
508.5	Fungus
509.4	Salt Fog
510.4	Sand and Dust
511.4	Explosive Atmosphere
512.4	Immersion
513.5	Acceleration
514.5	Vibration
515.5	Acoustic Noise
516.5	Shock
517	Pyroshock
518	Acidic Atmosphere
519.5	Gunfire Vibration
520.2	Temperature, Humidity, Vibration, and Altitude
521.2	Icing/Freezing Rain
522	Ballistic Shock
523.2	Vibro-Acoustic/Temperature

To pick examples:

- *Acoustic noise*

The required test condition for overall sound pressure levels and duration: Transport aircraft, in internal materiel bays close to jet exhausts: 140db for 30 minutes. High performance aircraft in internal materiel bays close to reheat exhaust and gun muzzles or in nose cones: 160db for 30 minutes. Within the engine these conditions occur together with severe thermal cycling.

- *Ingested matter*

Nobody can realistically expect that any conceivable measurement or actuation device will survive a direct frontal hit by a non-negligible size bird, pebble, hailstone or ice chunk. On the other hand fan blades of military jet engines very often show some marks of FOD after being operated in a real-world environment for a longer period.

Fig.8: Fan blades affected by ingested material.

It is well known that engines that are frequently operated in a dusty or salt fog environment suffer from accretions of the ingested material in certain locations in the compressors. Another troublesome consequence is the choking of cooling air holes of turbine blades leading to reduced cooling efficiencies and eventually to a reduced life time of the affected blades.

Fouling, sand deposits, blade erosion will have an influence on MEMS reliability, which is difficult to predict in the design phase. If it turns out that it is impossible with available (and affordable) technology to design and fabricate MEMS devices that are robust enough to survive and work reliably at locations in immediate contact with the main gas flow, one has to find ways to eliminate the need for direct exposure to the hot gas. One possible design alternative for flow control could be fluidic synthetic jet actuators, where the active element is "hidden" somewhere in the casing wall, perhaps combined with complementary pressure sensing.

- *Electromagnetic compatibility*

Since MEMS is essentially a surface technology the effects of electromagnetic interference have to be considered. Large areas of surface circuitry will be susceptible to EMI (either natural i.e. lightning or artificial e.g. radio transmitters, jamming, nuclear explosions).

Conclusion

Aero-engines are very complex technological products that operate in very demanding conditions. Their operations are dependent on these external conditions, which often affect their health and operating performance.

As a consequence an effort is being made to develop engines able to sense their environment as well as their own characteristics, and to influence them. MEMS sensors and actuators could be these technologies that give engine active perception capabilities and control functions to perform these tasks. Due to their size and their use in huge quantities offering redundancy and the potential for graceful degradation, they might also bring further reliability in jet engines.

Because of the new capabilities they would offer to future aero-engines, and due to the advantages they offer in term of weight and construction complexity, MEMS technologies are therefore regarded to be an increasing field of technical research in the aero-engines industry in the coming years.

However MEMS technologies are still quite young and do not give today sufficient levels of maturity and reliability to imagine short-term applications. The risks these technologies actually imply have to be strongly decreased to meet the aeronautical legislation standards, first step towards an industrial use.

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