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# OPPORTUNITIES AND CHALLENGES FOR MORE INTELLIGENT GAS TURBINE ENGINES

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**Abstract**

Modern aircraft propulsion systems have reached a high level of technology with respect to the individual design elements. However, making use of the immense potential of optimized adaptation and coordinated matching of the single elements has just begun. The concept of a more intelligent gas turbine engine aims at actively controlling engine operation to increase efficiency, durability and safety, while maintaining the high level of reliability required for aeronautic applications. Today engine manufacturers are investigating the potential of intelligent technologies for the next engine generation to meet the environmental challenges of an increasing transport demand and diminishing resources. This paper describes promising actively controlled systems currently on the brink of realization (e.g. Active Clearance Control, Active Surge Control, Active Flow Control, Active Nozzle Control) and details the respective opportunities and challenges. Active technology will require new types of actuators and sensors with inherent intelligence to be integrated in an advanced distributed control system. They are also expected to withstand the harsh conditions in a gas turbine, while meeting the exceedingly high standards of reliability typical for aeronautics. This paper will highlight the gaps between existing applications and the required technology. A likely roadmap for the development of smart systems in aircraft engines is outlined and ongoing activities will be presented.

## 1. INTRODUCTION

Modern aircraft engines face challenging requirements driven by customers' and public needs. A huge effort was spent over the last 60 years to reach a high level of efficiency in energy conversion. Generally the turbomachine shall provide high operational flexibility while maintaining a very high level of efficiency at low operation costs. The propulsion system must be capable to provide the required performance over a predefined mission throughout the entire service life. At the same time, it has to be affordable and safe. Growing attention is being paid to the environmental compatibility of the engine, which will become one of the most important aspects in future.

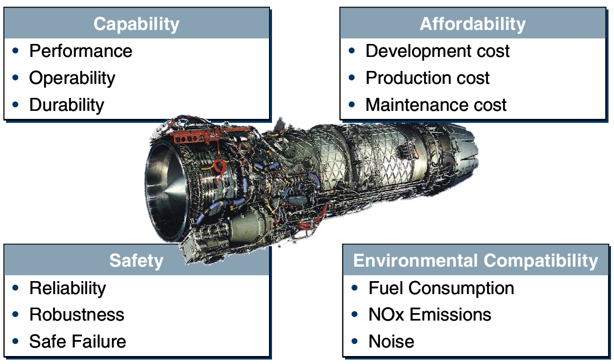


Figure 1: Requirements for a modern aircraft engine

To achieve these challenging targets, the engine has to operate at the physical limits given by material and gas properties. However, gas turbines also face a variety of constraints and operational requirements, including

- Inlet flow distortion and separation
- Compressor surge and stall
- Combustion instabilities
- Flow separations on airfoils
- Flutter and high cycle fatigue
- Engine noise.

These physical phenomena turn into design constraints because the engine has to be designed in a way to avoid instable or undesired operational conditions. Additionally to the physical boundaries they limit the available design space which could otherwise be used for a design optimization regarding the targets of Fig. 1.

Current engines use a limited amount of variables to control their operation. Thrust is controlled via a scheduled, non-dimensional parameter like engine pressure ratio or corrected spool speed, which sets the demanded fuel flow during steady-state operation. Variable guide vanes and bleed valves are used to improve the compressor off-design behaviour. While these devices themselves are controlled in a closed loop, the target parameter can only be regarded as being open-loop controlled because no feedback information on the current state is available. Besides the control of operation, existing sensors monitor the operational limits, but are rarely used as control inputs. In consequence, engines only respond to changing conditions which are recognised and covered by fixed control laws. Hence, the control action will basically result in a matching of the engine operating point to the thrust demand by taking into account ambient conditions under the constraint of engine limiters. To cover all relevant states, engine design is governed by the worst case operating condition and deterioration, which leads to large safety margins. The potentially available performance of engine components often is not exploitable due to different limits and rigid margins. As a result, the achievable engine performance is limited with current technology.

One way to overcome this situation is the use of active elements in gas turbine engines. While most avenues in the design process have been deeply explored the potential of control has still not been fully exploited. Extreme or deteriorated conditions can be covered by adapting the component to the current situation. Instable operating conditions can be avoided by changing the component characteristic. Thus the components can be optimized at the design stage without compromising performance by operational limits or singular events. An actively controlled engine will offer the best possible performance at any flight condition and point of time.

## 2. THE CONCEPT OF A SMART ENGINE

The key enabling technologies of a smart engine are active control, advanced diagnostics and prognostics. The idea behind active control is the ability to sense the current operating condition and state and to react with an adaptive control action. This leads to the basic principle of "intelligence": the component is aware of its current state and adapts itself to the current condition. An actively controlled component may be characterized as being self-diagnostic and self-prognostic. At the same time it is adaptive to optimize performance based upon the current condition of the engine or the current mission of the vehicle. The key to "intelligence" is the ability to not only sense but to interpret, and change pre-programmed actions or adapt based on that interpretation. The interrelated key functions of an intelligent engine are the management of engine performance and the diagnosis of engine health. This must be integrated into an intelligent control system based on smart sensors and actuators in a distributed, adaptive and fault tolerant architecture.

The traditional control design problem has been to transition the operating point of the engine from one point to another in the most expedient manner without compromising any predefined limits. The presence of full authority digital engine controllers (FADEC) on most modern aircraft offers the possibility to take advantage of more sophisticated control techniques. Presently an overriding concern for reliability still favours mechanically simple systems. Actuators, sensors and electronics have often been identified as potential sources for engine failures. However, the rapid progress of micro processing capability combined with advances in sensor and actuator technology, becoming cheaper, faster, smaller and, above all, more reliable, offer new possibilities of effective engine control.

In general, a control system consists of three essential sub-components: the sensor, the controller and the actuator. The characteristic of the system depends on the combination of these elements, which can be classified into three control approaches.

<u>Open-loop control:</u>
An open-loop control system consists of only actuator and controller. Due to its inherent simplicity, an open-loop system is very easy to implement. To determine whether the approach is adequate for a given system, an open-loop transfer function is required, which can be obtained experimentally or analytically. This step is considered most critical as the optimized performance depends on the fixed control action.

<u>Closed-loop control:</u>
A closed-loop control adds a sensor element to the open-loop control. The role of the sensor is to monitor the component in real time and actively modify the control action accordingly. Since a feedback action is required, the frequency response of the closed-loop sensor should exceed the operating frequency of the actuator and the controller. One of the key elements is the design of the controller, which needs to be stable and robust.

<u>Model-based / Adaptive control:</u>
Models can be integrated into the control loop to identify the systems state and derive prognostic actions. This offers completely new possibilities in engine control. On-board models may be used to provide engine parameters which cannot be measured directly due to the sensor location or their physical property. They may replace sensed parameters due to faults or low frequency response and can be used to predict upcoming events. Adaptive control refers to a self-adjusting controller that can modify the controller action depending on the transient external circumstance. An extra layer of control allows to adjust the closed-loop filter in a way that the control action is optimized for all conditions. Typically, the parameter that requires a change in the controller setting varies much more slowly than the closed-loop controller. An adaptive filter may require an additional sensor that provides transient response of the short-time averaged output, if the change in time-averaged parameters is not already known. A more extended view of an adaptive control system is a control system that provides a self-calibration.

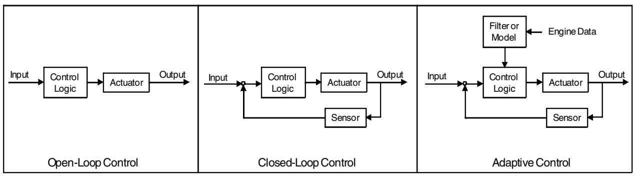


Figure 2: Different Control Approaches

The closed-loop and the model-based or adaptive control system can be considered as active control approaches. They can be extended by error checking procedures which prevent the system to generate wrong commands based on false conclusions.

An effective control relies on the existence of a low order phenomenon that control can affect. The sensor has to provide a signal which is adequate to characterize the system's state and capable to serve as a controller input. To accomplish this task, the sensor needs to be placed at the correct location and measure accurately as well as reliably. The actuator must be able to alter sufficiently the physical process. Control authority has to be large enough to change the system behaviour in all relevant conditions. This includes different ambient conditions as well as different operating points and has to consider real life effects as deterioration.

Depending on the component physics to be altered, three major actuation principles are available:

- Mechanical Flow Devices: Flaps, micro flaps, mechanical vortex generators
- Fluidic Actuator Devices: Blowing, suction, aspiration, transpiration, fluidic vortex generators, zero-mass-flow devices
- Structural Actuation Devices: Vibration damping, clearance control, shape changing and morphing techniques

A profound understanding of the physics is required to identify the mechanism which can improve component behaviour. The knowledge of the phenomena is the basis to establish models which are essential for controller design. A simplified but reliable model needs to be developed and applied which covers the major effects in the right cause-and-effect-chain.

The future of enhanced engine performance generally is seen as a highly multidisciplinary endeavour. Although a control system consists of many separate components it is essential to keep an overall systems perspective in mind when designing the subcomponents. The physical process is determined by the interaction of different phenomena and the interaction of individual elements. An interdisciplinary (fluids, control, structures, instrumentation, ...) approach is needed for success. An essential element in this process is a close collaboration between different specialists. In an industrial environment engine manufacturers have to cooperate with specialized sub-component suppliers supported by scientific resources.

During the NATO RTO/AVT128 Task Group on "More Intelligent Gas Turbine Engines" [1] a number of possible technologies illustrated in Fig. 3 have been identified for an application in a more intelligent aircraft engine.

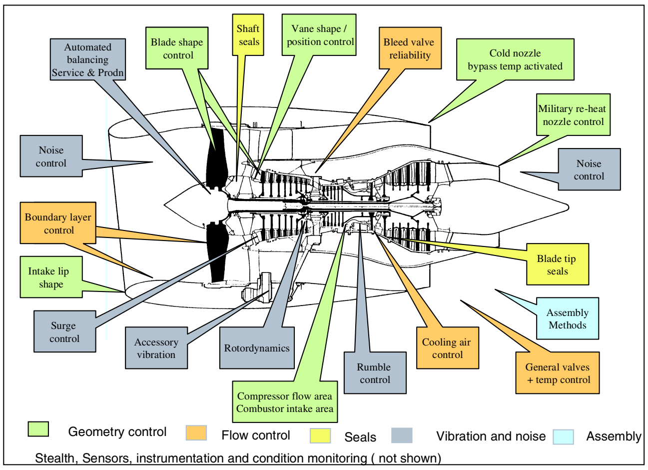


Figure 3: Potential active control technologies for a more intelligent aircraft engine [2]

## 3. NEAR-FUTURE APPLICATIONS

This section describes some promising applications of the smart engine concept. These technologies are currently at the development stage and are expected to reach technology readiness in the near future.

### 3.1. Active Clearance Control

Clearances represent one of the fundamental problems in turbomachinery. They are required to separate the rotating from the stationary structure but also represents an important source of aerodynamic losses and leakages in the turbine as well as in the compressor. Additionally, the compressor surge margin is negatively affected to a large extent. Blade tip clearances depend on the operating condition as the structure of casing, blades and disk expands with centrifugal force and temperature. Due to the different thermal behaviour of the structural elements a gas turbine transient causes a temporary variation in tip clearance.

The potential of active clearance control systems (ACC) has been realized some decades ago. Presently available systems are open-loop controlled based on the thermal expansion of the casing. Cooling air is blown on the structure to optimize blade tip clearance during cruise condition. The amount of air extracted from the bypass flow is scheduled as a function of one operating parameter, such as corrected speed or engine pressure ratio. Current ACC systems are not able to compensate transient clearance changes because of the thermal inertia of the casing and the missing link between actual clearances and amount of cooling air.

Innovative ACC systems are designed as closed-loop systems. By measuring the actual distance between rotating blades and stationary casing a signal can be generated which is fed through a controller to an actuator. The actuator adjusts the position of the casing, modifying clearance to an optimum level. The actuator may be designed as a thermal, mechanical or pneumatic acting device. The main advantage of advanced clearance control is the capability to react on any clearance change and thus counteracting transient effects as well as deterioration (Fig. 4). On overall engine level, specific fuel consumption (SFC) and exhaust gas temperature (EGT) margin are improved. The compressor characteristic additionally benefits from enhanced stability margin. An active clearance control system offers positive effects on fuel consumption, safety and reliability and maintenance cost.

The EU integrated program for NEW Aero engine Core concepts (NEWAC) is currently investigating different ACC concepts for the rear stages of a high pressure compressor [3]. While being mechanically complex, a fast acting, mechanical system using hydraulic actuators and variable liner segments as shown in Fig. 5 promises most benefit with respect to efficiency, surge margin, weight, cost, safety and reliability. The potential of a surge margin increase in the order of 10% and a specific fuel consumption reduction in the order of 1% has been identified.

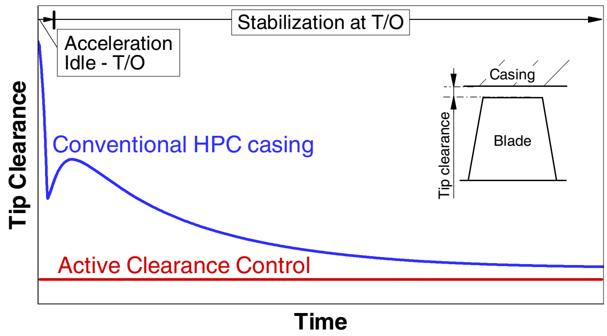


Figure 4: HPC tip clearance for an acceleration followed by a stabilisation at high power setting

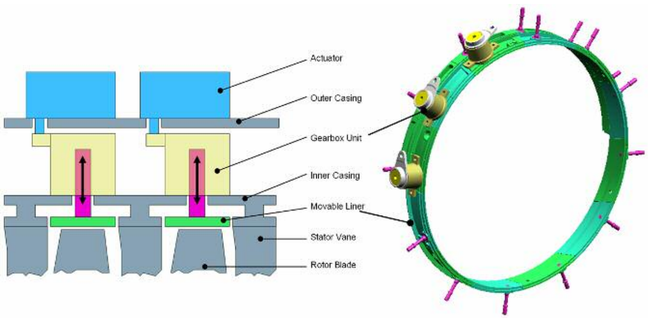


Figure 5: Schematic of hydraulically actuated mechanical ACC with adjustable liner segments [3]

The technological challenges for such a system lie in the hot environment, the need for almost complete elimination of leakage and play (caused by tolerances, thermal expansion and wear) as well as the weight and size of the overall system.

In order to create a "closed loop" system, clearance sensors should feature a robust design which withstands pressures and temperatures of the respective component gas path. Frequency demands are moderate as structural deformations take place in the timeframe of 1/10 seconds. Sensors and actuators have to consider non-axisymmetric clearances and fail-safe features to avoid rub-in.

### 3.2. Active Surge Control

Active Surge Control (ASC) has been a popular field of research in the recent years. The general feasibility of the technology has been proven in different compressor and engine demonstrators. The basic principle goes back to the possibility of detecting flow conditions close to the compressor stall point and counteracting by blowing, guide vane movement or de-throttling.

When approaching an aerodynamic instability a compressor develops stall precursors: high frequency pressure and velocity fluctuations which can be measured by pressure probes or hot wire sensors. The time between the measured precursor and the stall or surge event depends on the aerodynamic nature of the instability. In extreme cases a time delay of only a few milliseconds has been observed. Therefore, it is very challenging to measure and react on a characteristic unsteady disturbance which leads to compressor stall.

Monitoring of the compressor operating point offers another possibility to detect the proximity to stall. Due to the unknown actual surge line position at any point of time threshold values with incremental safety margins have to be used with this approach.

Based on the detected stall condition different possibilities of counteracting and extending the stable operating range have been proposed. One of the promising technologies consists in injecting air through discrete holes in the casing with high velocity into the tip gap of the compressor blade. The feasibility of extending the operating range by tip injection has been demonstrated in several compressor rigs as well as in complete engines. The achieved benefit depends on the design of the injection system and the control algorithm which is used for the specific application. An increase of surge margin in the range of 25% compared to a solid casing has been demonstrated [4].

European aero engine manufacturers are currently working in NEWAC on the integration of air injection into their high pressure compressors to improve stability at part power conditions (Figure 6).

Another approach to extend the compressor's operating range is the quick adjustment of variable guide vanes. The modulated actuation of single vanes produces a travelling wave around the annulus which stabilizes the flow in the compressor. A specially designed controller couples the actuation mechanism to a sensing unit, providing a suitable modulating frequency and quick reaction to unstable conditions.

A third method uses fast acting bleed valves to stabilize the compression system. While conventional bleed ports only influence the operating point of the compressor stages these systems aim on improving their surge line. The dynamic opening and closing of the bleed valves behind the compressor changes the dynamic behaviour of the system. Specially designed controllers are able to operate the compressor in its conventionally instable regime.

Active surge control offers two major advantages for a gas turbine. A direct benefit is given by the enhanced stability

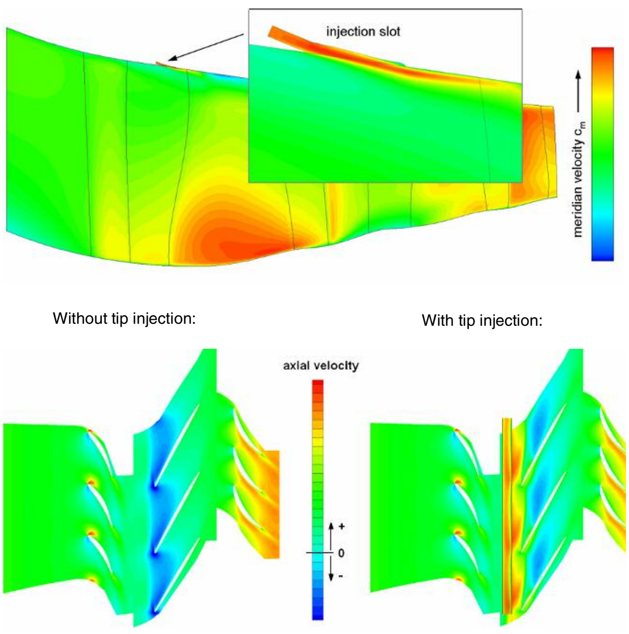


Figure 6: Cross section through a flow field near the surge line with tip injection (top) and reduced blockage close to the casing wall as result of the injection (bottom) [3]

of the compressor. This additional margin may be used to close existing lacks of stability or to tighten operability requirements through quicker engine acceleration and deceleration or additional allowances for inlet distortion. An additional benefit can be gained by addressing the compressor design. If parts of the surge margin stack up could be provided by active systems only if required, the basic stack up would allow for lower incremental surge margin. This would release new design space which can be used to optimize overall performance, component efficiency and parts count (airfoils or stages) and thus production and maintenance costs.

## 3.3. Active Flow Control

Some aerodynamic principles of flow control have already been known since the 30s of the last century. Better understanding in flow physics, improved manufacturing technologies and the demand of efficiency and operability increase enforces the application of active flow control techniques today.

The flow control technology aims mainly at an active improvement of local boundary layers. These have the disadvantage of being the dominant source of aerodynamic losses in turbomachines and can lead to a detachment of the flow. Different actuating devices have been developed and successfully been tested. Applications focus on the engine intake and compressor front stages but have also been proposed for the turbine and the nozzle. The performance potential is assumed to be significant. Propulsion system studies show a possible $CO_2$ emission reduction relative to today's level of 2-3% for compressor and 4-5% for turbine applications [5].

The first group of flow actuation manipulates the boundary layer by blowing or suction. Transpirated or aspirated blades and platforms are equipped with rows of small holes through which air is ejected or extracted. Both mechanisms stabilize the boundary layer which would otherwise detach. The method extends the operating range of a compressor stage significantly or enables a blade count reduction of about 10-20%. Depending on the requirements the air bleed can be switched on and off.

A special configuration of the method is the application of a few pulsed jets on the suction side of a blade in order to delay the separation at part speed. The pulsed jets can be designed based on zero-mass-flow devices (synthetic jets), on high speed micro valves (actuation frequency in the order of a few hundred Hertz, hole diameter in the order of a millimetre), on the basis of plasma jets (generated by high voltage beam) or on micro-combustion where a small amount of fuel is burned inside a small cavity beneath the blade surface.

To investigate the impact on loss generation a wind tunnel test has been carried out in the European research project ADVanced ACTuation Concepts (ADVACT). Jets have been used to control a turbulent trailing edge separation on a flat plate that simulates the pressure distribution of a compressor blade suction surface. A loss reduction of 36% has been achieved with steady blowing jets [6].

For this application, the MEMS technology plays an important role due to their small size, low cost and low-energy consumption. It furthers offers the opportunity to integrate sensing, actuating and processing functionality at length and timescales of the flow to be controlled. Due to reliability and robustness considerations the first applications of fluidic actuation devices are realistic for low temperature engine components. An example of a micro-actuator to be used in an active flow control loop has been demonstrated in ADVACT [7]. A micro-magneto-mechanical system (MMMS) produced high flow rate pulsed micro-jets in a wind tunnel experiment that could successfully suppress boundary layer separation.

Airfoil shape change, especially by using shape memory alloys (SMA), is another method to adapt the blade geometry to the operating point. The incidence/deviation angle of the flow increases/decreases as the compressor operates at lower mass flow rates than design conditions. A blade can adapt its shape to the current aerodynamic conditions by activating the shape memory alloy effect. The difficulty in applying this technology is the generation of the phase change temperature which initiates the effect (Fig. 7). Currently available SMA materials have a transition temperature of about 100°C. In the near future SMA material with phase change temperatures of about 500°C…800°C can be expected.

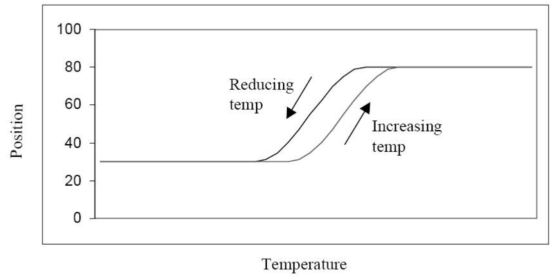


Figure 7: Position/ shape control by SMAs [8]

The application of vortex generators which consist of a small piece of metal sheet mounted inclined to the flow is well known for wings and intakes. An active application reduces the losses of a permanently installed device. Deployable vortex generators can be used in a gas turbine to reduce aerodynamic losses and to avoid flow detachment. In contradiction to passive aerodynamic devices active flow control offers a negligible impact on efficiency because it is only deployed when needed.

## 3.4. Active Nozzle Control

The nozzle of a jet engine offers several opportunities for active control: Noise reduction, fuel consumption improvement and surge margin enhancement.

Active noise reduction has been a popular area of technology development the last couple of years. One of the noise reduction options currently considered is the chevron nozzle. The chevron nozzle aims for more rapid mixing of the main engine flows to reduce the shear layer, which generates noise due to jets at different speeds. Flight testing demonstrated the effectiveness of serrations for noise reduction, but also shows a performance penalty driven by the nozzle geometry.

Since noise reduction is only needed at very low altitude, work has been ongoing to implement shape memory alloys in chevron nozzles for the outer nacelle of an aircraft engine, which will withdraw the serrations at altitude. Shape memory alloys have the unique characteristic that they can be trained to change shape at a specific temperature. Thus for take-off the chevron nozzle can be one shape and then once out of noise sensitive regions they can be another for aerodynamically efficient shape.

Fluidic injection may be an alternative to mechanical chevrons. Here, noise reduction is achieved by a fluid dynamic effect with injected flow. Again, this has the advantage that it can be turned off when not needed.

The signal for the nozzle adaptation can be generated from an adequate engine operating parameter as flight altitude, flight Mach number, corrected speed or engine pressure ratio. Using SMA's, the bypass air temperature can directly serve as a control signal. Air temperature naturally reduces with increasing altitude. The primary challenge is to produce an SMA based system which is capable of providing sufficient operational stiffness and high movement whilst still being cost effective and safe.

An adaptive nozzle may also serve as an actuation device to control engine operation. By changing the nozzle throat area the thermodynamic cycle of the gas turbine can be modified and optimized for different operating conditions. This concept is already in use for afterburner control in military jet engines. For commercial high bypass turbofans it offers the possibility to control the fan operating point. A relatively small area change can result in significant benefits in performance and fan surge margin. During take-off the engine matching can be optimized for high thrust, during cruise for low fuel consumption and during approach and landing it can be adjusted to low noise settings.

Significant improvements in fuel burn and component life become exploitable if this kind of nozzle control is combined with a reliable real time instability detection. By increasing the degree of freedom in positioning of the working line of the compressors, the thermodynamic cycle can be optimized without the restrictions of rigid compressor stability safety margins. Hence the operating point of the compression system is adaptable to the actual operation condition of the aircraft. Such a system has been successfully demonstrated by MTU on a military jet engine and will be ready for application in production engines in short term.

The technology is based on the concept of raising the working line of the compressor towards increased efficiency by reducing the available stability margin at predefined operating conditions. Once an upcoming instability is detected (surge pre-cursor), the controller commands a temporary increase of the nozzle throat area in order to lower the working line accordingly. As soon as the situation is stabilized, the throat area reduces again to the pre-defined lower value to improve engine performance.

This nozzle control system was successfully demonstrated in a military jet engine by optimizing throttle area at certain operating conditions. Different transient manoeuvres have been tested with and without activated control. Figures 8 and 9 show an example of the results. In Fig. 8 the control is deactivated and a stable acceleration is not feasible with reduced nozzle throat area. When surge occurs, a drop in shaft speed evolution can be observed.

Once the control is activated, the engine is accelerating smoothly (Fig. 9). When the first indications of upcoming instability are detected, the controller reacts by opening the throat area and the engine accelerates as demanded.

An advantage of an actively controlled nozzle is its comparably low temperature and structural simplicity. Any active device would be easy to install and maintain while operating at moderate conditions. This makes active nozzle control one of the near future applications.

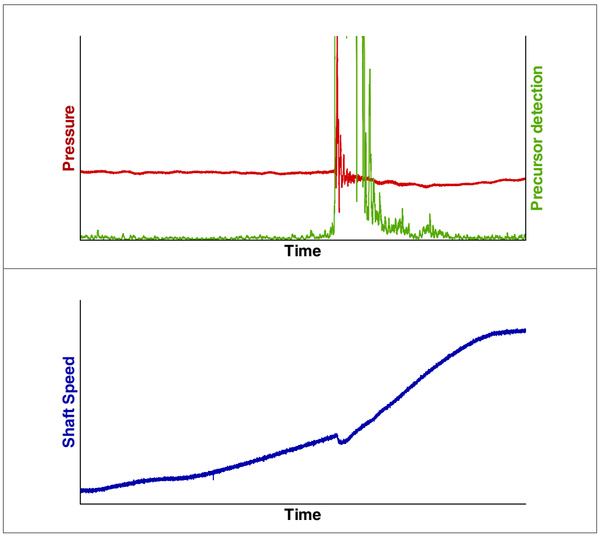


Figure 8: Acceleration without nozzle control

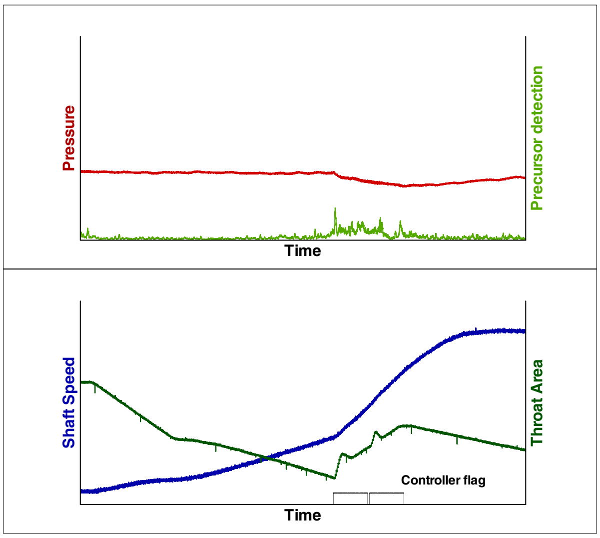


Figure 9: Acceleration with activated nozzle control

## 4. WAY FORWARD

A more intelligent engine offers promising opportunities. However, an airworthy application ready to entry into services can only be achieved by an improvement of the state-of-the-art technology.

### 4.1. Sensors

The sensors play an important role in an active control system. Latest sensing technologies still show a gap between available applications and the requirements of an active system in a more intelligent aero engine. The operating environment is harsh and especially the temperature level is extremely challenging as illustrated in Fig. 10.

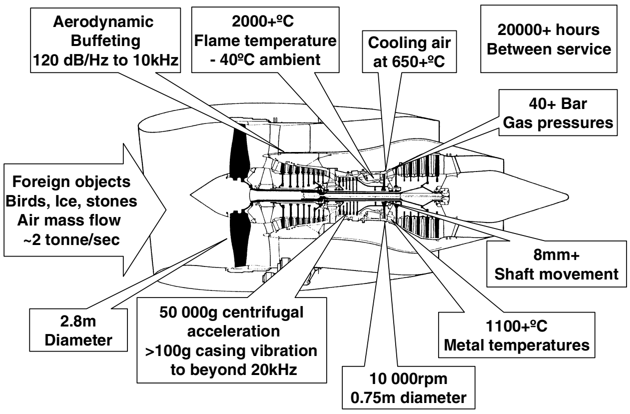


Figure 10: Environment within an aircraft gas turbine engine [2]

By changing design and packaging of current sensors, operating environments of 750°C may be possible, which would meet requirements for sensors located towards the engine intake. However, sensors for locations close the engine combustion chamber or afterburner with operation temperatures up to 1700°C do not exist.

Micro-electronic mechanical systems (MEMS) address the need for high-temperature operation and smart sensor capabilities. MEMS integrate electronics with sensing and signal processing at the chip level and provide advantages such as low mass, high reliability, low power consumption and low cost. New materials like the semiconductor silicon carbide (SiC) and the ceramic silicon carbide nitride (SiCN) offer the opportunity to operate in a high temperature environment. Prototypes are foreseen to be available by 2015 – 2020 [9].

As the closed-loop control system relies on the input signal, the sensor's reliability needs to be close to 100%. Taken the long life cycles of an aero engine, this represents a challenging task. This target can still not be met by existing technology and more development work is required. The strategy of redundancy can be applied to enhance the reliability of the sensed signal. This approach will only be feasible if sensor cost will be reduced and the devices are installed at an easily accessible location.

In the case of the ACC system described above capacity probes can be used. As these sensors are not reliable enough and often fail under engine conditions, new technology is required. The European technology program DREAM (valiDation of Radical Engine Architecture systeMs) targets on the development of a smart active clearance control system to improve turbine running clearances for all relevant flight conditions for new and deteriorated engines. In cooperation with the high-tech sensor manufacturer Vibro-Meter an innovative clearance sensor based on microwave technology will be investigated. Besides clearance sensor development the project focuses on optimization of the ACC module (new light weight design, increasing impingement heat transfer), the control unit as well as testing of the overall system for typical engine conditions.

The majority of state-of-the-art sensors used for engine monitoring focus on the measurement of pressure and temperature. For ASC and AFC, fast pressure transducers can be integrated into the active control system. These devices are successfully used in development engines and demonstrators but are limited to the temperature level of compressor front stages. The measurement of other physical properties like velocity gradients or shear stresses is sometimes more appropriate to describe internal conditions of a fluid flow. The introduction of optical measurement techniques is advisable due to their non-destructive measurement principle. Furthermore, sensing technologies like turbine emission species sensors, burning patter factor sensors, fuel property sensors and exhaust gas composition sensors are of interest for more intelligent gas turbine engines. In addition, smart sensors which would enable future distributed control architectures are being explored.

## 4.2. Actuators

The design of the actuator is a challenging task. Engine applications require high durability at low size, weight and cost. Existing solutions do not fulfil all four criteria.

As the control system fully relies on its functionality and authority, the actuator must be robust and reliable. A lot of applications have been demonstrated at laboratory scale but need to prove their technology readiness under real engine conditions. As 100% reliability seems out of reach, failure cases already need to be covered by the design. If the actuator fails the engine must be capable to operate in a safe mode (fail-safe). As an example, the ACC actuator shall be designed to open up tip clearance rather than to close and destroy blades. Further progress is required in terms of weight and robustness.

Additionally, closed-loop devices need to operate at high frequencies and respond very accurately. Progress is expected from new materials and better manufacturing processes. Design tool development needs to support this step.

ASC actuators often consist of valves. As instability may occur very quickly, the operating frequency needs to be improved compared to existing hardware. MTU is currently setting up a compressor rig test to validate a very fast acting high temperature valve for an aero engine application. The valve shown in Fig. 11 has been designed and manufactured by Parker Aerospace Air & Fuel Division. It controls an injection air flow based on piezo electric actuation at a rate of <3ms from fully closed to fully open.

The actuator's energy requirement has to be fed by a link to a power source. A wired link for power and information

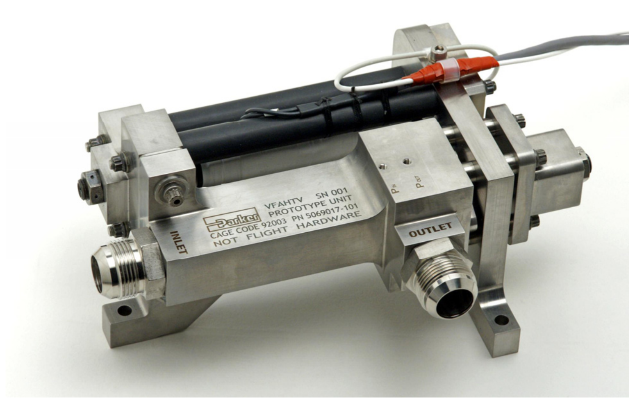


Figure 11: The Parker Aerospace Very Fast Acting High Temperature Valve

transmission is not always feasible due to design and reliability considerations. Advanced solutions like infrared or wireless connections can be set up for information but the generation and transmission of power is still an open question. Promising concepts have been proposed based on magnetic or electric fields. The preferred solution is the power generation at the location of the power consumer. An aero engine has the potential to provide various energy sources at a very high level of energy density, e.g. local velocity, pressure or temperature gradients. The total energy requirement of the actuation system has to be considered very carefully. An actuation system which needs more power to introduce additional energy into the system than the net benefit is not suitable for an active control system.

The biggest challenge for smart devices is the integration into the component. This requires small, lightweight and robust actuators and the miniaturization of current applications. Established actuators such as hydraulics, electrical and even fluidics still offer considerable opportunity for future developments. Advanced concepts will be designed as MEMS based on new technologies like electro active materials (piezo electric ceramics, electro active polymers), shape memory materials or magnetic strained materials.

## 4.3. Control system

Linking a sensed signal in a closed loop to an actuation device is a common task. The challenge for active control arises from the interpretation of the input signal and the choice of an adequate control action. The basis for a design of a smart control system is a profound understanding of the physical process. It has to be derived by both, testing and simulation. Capturing the physics in experimental tests requires advanced and accurate measurement techniques. In many cases the identification of real geometry physics and the corresponding system behaviour represents a challenge, especially when dynamic processes need to be quantified. The test results contribute directly to the physical understanding and provide the source for validation of sophisticated tools and models. Running a calibrated model is much more effective than to carry out a series of tests. Simulation can help to identify physical phenomena which cannot be measured because of their location, dimension or unsteadiness. Modern designs rely entirely on the use of computational methods which opens up a range of new possibilities. For active control, an adequate model is required to design the control system. Advanced numerical simulation methods are essential to achieve the desired results.

Better integration of tools and processes are required to meet the opportunities and to be able to exploit the advantages of active control technology. With the introduction of more intelligent engines the development process will change from established best practice rules to an individual design optimization. The design engineer needs to have highly integrative skills as well as expert knowledge in different fields of aeronautical engineering. He will need fast, accurate and integrated tools to perform this task. The engine can only be as “intelligent” as its designer.

Presently, the engine control system architecture is based on a centralized design in which sensors and actuators are directly linked to an engine-mounted control unit. This approach will not be feasible for a smart engine because of weight and volume considerations. Future control systems will feature a distributed architecture, where a large number of elements are connected through a common, standardized communication interface (Fig. 12). Control nodes coordinate a stream of information in a communication network. This design also enables the integration of intelligent sub-systems.

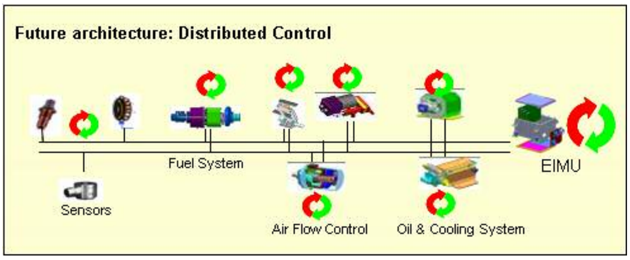


Figure 12: Distributed Control Architecture

The control system has to cover not only normal operation but also any faults in the chain of sensing and actuation. Using redundant elements, the controller needs to choose the correct signal, but this approach is not very effective in terms of cost, weight and space. More sophisticated solutions use onboard-models to analyze the current engine or component condition. These models offer a broad spectrum of applications, reaching from pure monitoring to full model-based control. It may even replace sensors at locations difficult to access or provide parameters which cannot be measured. The challenge is here to individualize the general model to a specific engine. This approach will lead to the transition of the control system design from a Single Input Single Output (SISO) control loop for main fuel and schedules for the variable geometry actuators to more advanced model-based Multi Input Multi Output (MIMO) control architecture, where all available control actuators are coordinated to achieve multiple objectives

An example is given by ASC which relies completely on the detection of stall precursors. If the sensor fails or the precursors are not detected because the flow properties have changed, the engine will surge. An exact surge margin tracking system can replace the critical sensors, while relying on parameters which are easy to measure. It can launch actuation early enough to avoid any instable condition before it occurs. In the same way, onboard models may be used in ACC, AFC and ANC systems but better concepts need to be found.

Besides the potential for engine performance, the new technologies have to fulfil all the airworthiness, safety and durability requirements of today’s engine generation. System reliability remains one of the biggest challenges. The clear target of a more intelligent engine is a net gain in reliability while increased functionality is obtained through the addition of complexity.

The first in-service applications of active control may focus on efficiency and noise without touching any safety critical item. A pilot may rather accept to fly temporarily at reduced performance, e.g. higher fuel consumption or louder engine, than to compromise safety. This favours systems like ACC and ANC when used for efficiency and noise optimization compared to ASC and AFC, which would require full reliability.

For engine manufacturers and customers the economical side also plays an important role. Taken the development, production and maintenance cost into consideration, the performance potential of a more intelligent engine is currently compromised to a large extent. Active control systems will only find their way into service if the systems get affordable. Manufacturers need to find attractive solutions in close collaboration with component suppliers on the technical and economical side.

## 4.4. Product evolvement

Technology evolution at MTU Aero Engines is guided by a well established process that clearly targets towards product application. From the very beginning on innovative ideas are rated not only by peers but also by experienced product managers. Therefore questions beyond the pure technical aspects are raised and followed throughout the technology development phase. At predetermined milestones the economic perspectives are balanced against the strategic product roadmaps to pinpoint targets and timeframe for a first application.

Regarding Intelligent Gas Turbine Engines MTU Aero Engines has identified three areas of activity shown in Fig. 13.

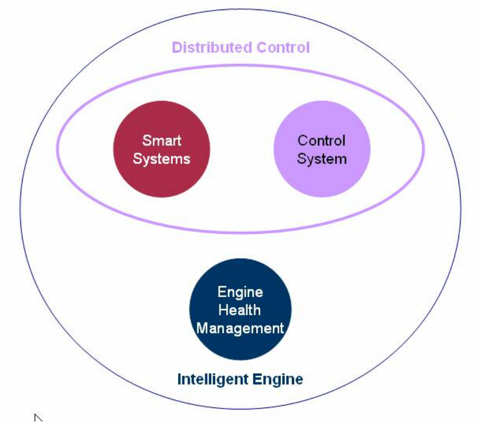


Figure 13: Intelligent Engine – Technology Fields

As illustrated in the previous chapters, MTU has followed and still pursues manifold research activities in the vast field of “Smart Systems”. These kind of mechatronic components currently experience a progressive expansion in the application range from automotive chassis actuation to the alpine ski with adaptive flexibility. Driven by those industrial needs the maturity of mechatronic systems is growing so fast that the reliability required for aeronautic applications comes into reach within the next decade.

Engine control is a traditional domain of MTU Aero Engines. Building on that experience MTU is currently enforcing technologies needed for distributed control architectures like bus systems and electronic functional elements (Fig. 14), particularly designed to tolerate hot and harsh environment conditions.

The first step of an intelligent engine is being done today by adding sensing capability for monitoring purposes. The quality of control depends strongly on the accuracy and granularity of the available status information. More intelligent engines will therefore benefit directly from any accuracy progress in the vast field of sensors – given that the new technology can stand up to the hostile environment encountered with aero engine applications.

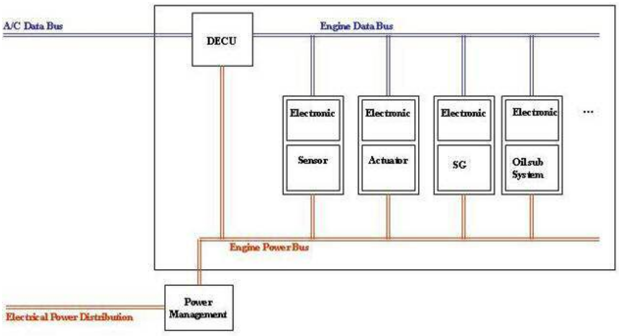


Figure 14: Engine Network Data Communication

As an example, MTU is cooperating with the experienced sensor manufacturer Vibro-Meter within the already mentioned NEWAC research program to develop a fast responding robust pressure sensor for compressor stall detection.

Apart from the accuracy it is likewise complex to improve the amount of available engine status information as weight, size and cost limits prohibit increasing the number of installed sensors. Here the method of choice is substituting measured data by calculated values from accurate, individualized and adaptive engine models. Currently there are no standards to certify confidence levels required for using complex engine models in safety critical control applications. An improvement of maturity regarding the existing types of models is required before model based engine control will be seen to fly. MTU currently promotes engine model improvements in conjunction with diagnostic and prognostic monitoring features.

Complex monitoring capabilities are gaining importance regarding maintenance costs and fleet management. MTU Maintenance Hannover is already supporting MRO customers with an in-house Engine Trend Monitoring System that can be tailored to the individual applicants profile (Fig. 15). The system is based on a full thermo-dynamic engine model. Currently deterioration prognostic and modular diagnostic technologies are refining the system. The final product, being in this case the improved customer service, is phased in parallel with software upgrade.

The demonstration in a real engine is the final step of transferring technology to the product. While the feasibility of active technologies has already been shown in lab-

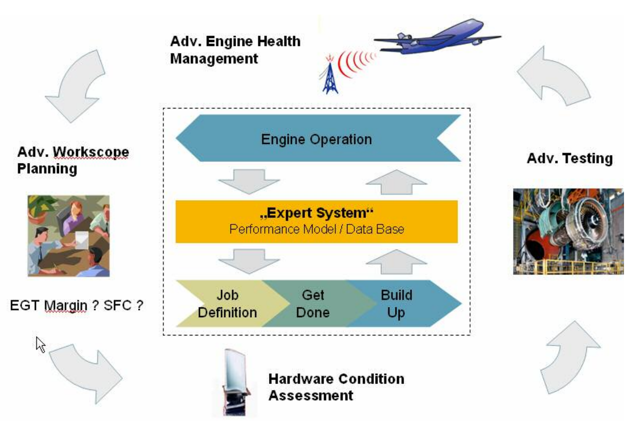


Figure 15: Intelligent health management by Engine Trend Monitoring

scale demo tests, a huge effort in research and development has to be spent to demonstrate the feasibility of these technologies in a real engine environment. Besides a broad engine test know how a high degree of interdisciplinary is needed when validating intelligent engine features. Therefore, MTU Aero Engines has set up a center of competence “More Electric Engine” at the University of the Armed Forces in Munich in 2007. A MEE demonstrator engine is currently being set up at the engine test facility of the Jet Propulsion Institute in a basic configuration, that will be gradually upgraded with the intelligent components to be validated.

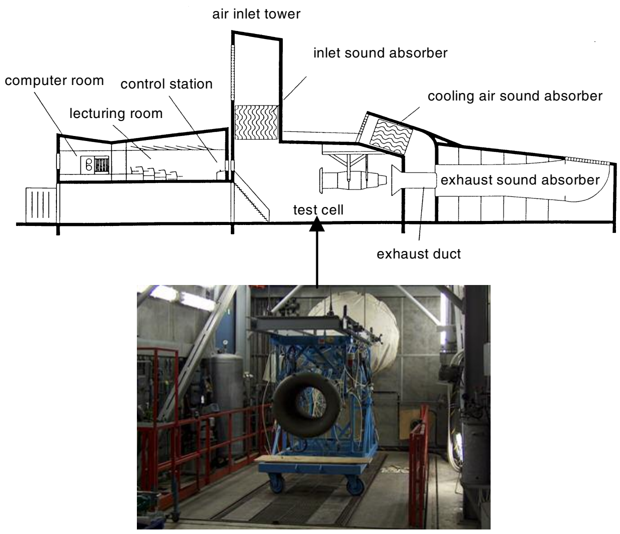


Figure 16: Engine Test Facility, Jet Propulsion Institute, University of the Armed Forces

## 5. CONCLUSION

The design and control philosophy of modern aircraft engines based on operational constraints and rigid margins limits the achievable engine performance with current technology. More intelligent engines offer the opportunity to enhance capability, environmental impact, safety and affordability. Actively controlled components will diagnose their current state, predict upcoming events and adapt their characteristic towards the requirement.

A choice of active control applications is described in this paper. Active Clearance Control, Active Surge Control, Active Flow Control and Active Nozzle Control offer promising opportunities and will be realized in the near future.

Despite promising advances in sensor and actuator technology, challenges remain in terms of the harsh operating environment in the gas turbine, the performance requirements, the high level of reliability and the integration into the engine with acceptable size, weight and cost. Advanced control system architectures and sophisticated models and tools will be needed to coordinate the sub-systems in a distributed, multi-parameter way.

Due to an increasing number of public and industrial technology projects the required step of progress comes into reach. Prototypes already demonstrated the feasibility of active systems and extended monitoring capabilities have become available.

MTU Aero Engines is advancing the product evolvement by intensive research and development activities in the fields of smart systems, innovative control architectures and engine health management.

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