Chapter 2 – ACTIVELY CONTROLLED COMPONENTS

by

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ABSTRACT

Active Control can help to meet future engine requirements by an active improvement of the component characteristics. The concept is based on an intelligent control logic, which senses actual operating conditions and reacts with adequate actuator action. This approach can directly improve engine characteristics as performance, operability, durability and emissions on the one hand. On the other hand active control addresses the design constrains imposed by unsteady phenomena like inlet distortion, compressor surge, combustion instability, flow separations, vibration and noise, which only occur during exceptional operating conditions. The feasibility and effectiveness of active control technologies have been demonstrated in lab-scale tests. This chapter describes a broad range of promising applications for each engine component. Significant efforts in research and development remain to implement these technologies in engine rig and finally production engines and to demonstrate today's engine generation airworthiness, safety, reliability, and durability requirements. Active control applications are in particular limited by the gap between available and advanced sensors and actuators, which allow an operation in the harsh environment in an aero engine. The operating and performance requirements for actuators and sensors are outlined for each of the gas turbine sections from inlet to nozzle.

2.1 INTRODUCTION

This chapter describes potential applications of actively controlled components in more intelligent gas turbine engines. The text starts with general considerations on objectives and high level approaches of the technology. The second section lists various active control applications ordered according to the typical gas path of a gas turbine: inlet, compressor, combustor, turbine and nozzle. The chapters conclude with specific requirements for sensors and actuators needed for the individual technologies.

2.2 GENERAL IDEA OF ACTIVE CONTROL

Modern aircraft engines face challenging requirements driven by costumers' and public needs. A huge effort was spent over the last 60 years to reach a high level of efficiency in energy conversion. However, the design of a turbo machine requires numerous design compromises to meet the technical requirements. Generally the turbo machine shall provide a high operational flexibility (large operation range) while maintaining a very high level of efficiency at low operation costs (e.g. large maintenance cycles). The propulsion system must be capable to provide the requested performance over a predefined mission throughout the entire service life. At the same time, it has to be affordable and safe. Growing attention is paid to the environmental compatibility of the aero engine, which will become one of the most important aspects in the future.

To achieve these challenging targets, the engine has to operate at the physical limits which are 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; and
- Engine noise.

These unsteady phenomena only occur at exceptional operating conditions, but turn into design constraints since they have to be avoided. Additionally to the physical boundaries they are limiting the available design space which could otherwise be used for a design optimization regarding the overall targets of Figure 2.1.

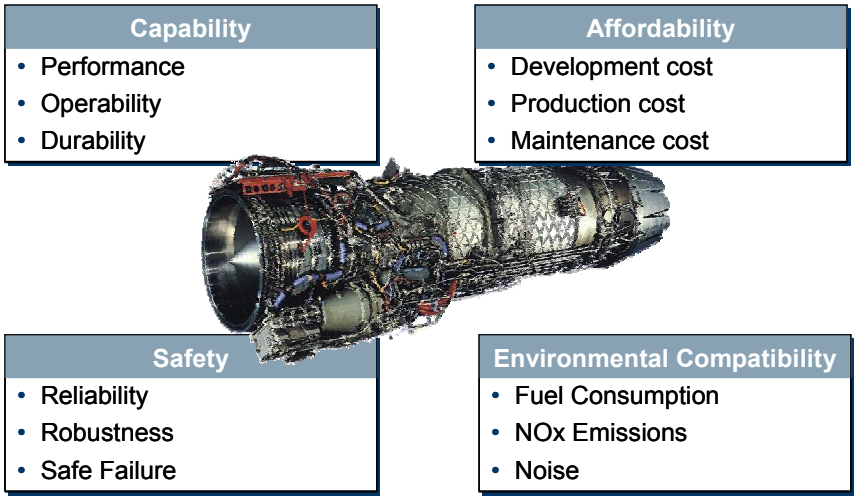

Figure 2.1: Requirements of a Modern Aircraft Engine.

Current engines are open-loop devices because of limited onboard computational capacity, relatively poor sensor technology and overriding concern for reliability, which favors a mechanically simple system [2.1]. In consequence, these engines are unable to respond to changing conditions. Because of this inflexibility, their design is governed by the worst case deterioration and operating condition which leads to large safety margins. Presently the potentially available performance of engine components often is not exploitable due to the fact that different limits and margins have to be taken into account during the design [2.2]. As a result, the achievable engine performance is limited with current technology [2.3].

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. The future of aviation propulsion systems is increasingly focused on the application of control technologies to significantly enhance the performance of a new generation of air vehicles. The idea behind active control is the ability to sense the current condition and to react with an adequate control action. This leads to the basic principle of intelligence: the component is aware of its current state and reacts if necessary to improve its 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 [2.4]. Instable operating conditions can be avoided by changing the

component behavior. Extreme or deteriorated conditions can be covered by adapting the component to the current situation. Thus the components can be optimized at the design stage without compromising performance by operational limits or singular events. Furthermore, an actively controlled engine will offer the best possible performance at any flight condition and point of time [2.5]-[2.8].

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 [2.4]. The presence of full authority digital engine controllers (FADECS) on most modern aircraft offers the possibility to take advantage of more sophisticated control techniques. The rapid progress of micro processing capability combined with advances in sensor technology, becoming cheaper, faster, and smaller, offer new possibilities of effective engine control. While macro-scale actuation still evolves slowly, micro-scale actuation is changing rapidly and power electronics are getting cheaper. Also an increased use of sensing and actuation across networks can be observed in modern propulsion systems. Advances in sensing technology and the insertion of this technology into next generation aircraft propulsion systems will enable the transition from conventional control logic to advanced adaptive control, making the vision of intelligent aircraft engines a reality. 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 [2.8]. The first step of an intelligent engine is being done today by adding sensing capability for monitoring purposes. This approach is leading to the desire to alter the observed component behavior. An improved physical understanding and additional modeling capability is supporting this process.

In general, a control system consists of three essential sub-components: the actuator, the controller and the sensor. The characteristic of the system depends on the combination of these elements. The layout can be classified into three control approaches [2.8], [2.9]:

- **Open-Loop Control:**

  An open-loop control system consists of only actuator and controller. The actuator must be able to alter sufficiently the physical process. 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.

- **Closed-Loop Control:**

  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.

- **Adaptive Control:**

  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 one to adjust the closed-loop filter in such 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.

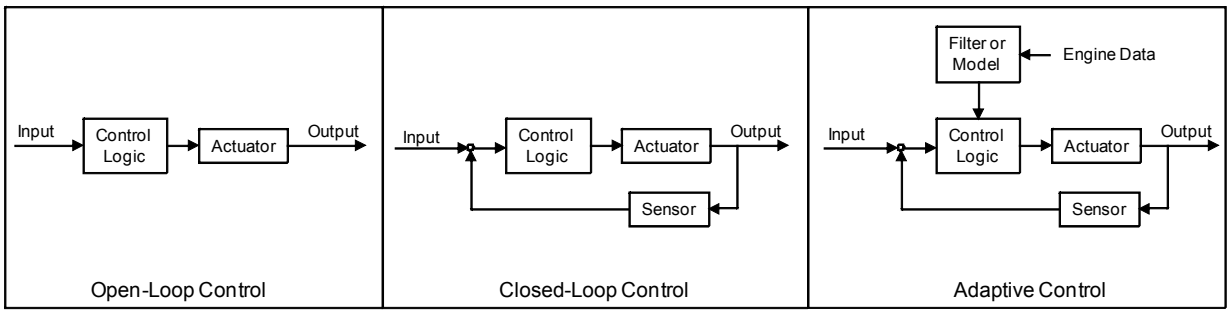

Figure 2.2: Different Control Approaches.

The closed-loop and the 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 (e.g. due to the malfunction of a sensor). On-board models may be used to provide engine parameters (virtual sensor) which cannot be measured directly due to the sensor location or their physical property and to predict upcoming events. Chapter 3 of this report describes the engine control concepts in detail.

An effective control relies on the existence of a low order phenomenon that the control can affect. These phenomena have to be unsteady to be stabilized by the control action. In consequence, actuator and sensor placement is critical. A profound understanding of the physics is required to identify the mechanism which can improve the component behavior. The knowledge of the phenomena is the basis to establish simplified models which are essential for controller design. If a consistent physical model is not available due to its complexity, a simplified but reliable model is necessary to be developed and applied which covers the major effects in the right cause-and-effect-chain. To capture the critical system dynamics in these models again a deep understanding of the physics is required [2.8]. While the simplest model may fail in prediction of the correct cause-and-effect-chain, the most complex model may require human and computational resources beyond today's availability. Therefore, it is in the responsibility of the design engineer to evaluate and select the most appropriate method to design a suitable actuation system.

The component behavior can be characterized by detailed testing and modeling. Despite fascinating advances in simulation, both methods need to be carried out. 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 behavior 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 tools and models. Sophisticated tools and models are indispensable for component analysis and design. They can identify physical phenomena which cannot be measured because of their location, dimension or unsteadiness. Running a calibrated model is much more effective than to carry out a series of tests. 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. New and more sophisticated methods may be needed to achieve the desired results. Due to the increased demand of the improved physical knowledge the introduction and application of advanced numerical simulation methods are essential. However, the development of advanced numerical methods requires more research and development effort but promises the derivation of more reliable control laws and rules. Considering the field of aerodynamics following numerical methods are under consideration (with increasing level of complexity):

- Standard turbulence modeling (e.g. one-equation, two-equation turbulence modeling as k-ω, k-ε or Spalart-Allmaras model);

- Advanced turbulence modeling: Detached Eddy Simulation (DES), Large Eddy Simulation (LES); and
- Direct Numerical Simulation (DNS).

An interesting idea in this context is that knowledge can flow in two directions [2.10]. First, information is gathered from various disciplines to enable the development of an actively controlled component. Second, the controlled component is actually a new diagnostic tool for exploring component characteristics and can thus offer new information for design.

Another important aspect of active control is its system nature. Although a control system consists of many separate components it is essential to keep an overall systems perspective in mind when designing these subcomponents. The physical process is determined by the interaction of different phenomena and the interaction of individual elements. Adding feedback control can change the system dynamics and a controlled component can have different properties. An interdisciplinary (fluids, control, structures, instrumentation, ...) approach is needed for success because the systems aspects are critical [2.10]. 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.

The sensors play an important role in an active control system. They have 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. Latest sensing technologies enable the intelligent engine vision, because the sensors are small and robust enough to collect the data required for engine control and health management. Today's aircraft engines are typically equipped with a suite of control sensors (temperatures, pressures, rotors speeds, etc.), the outputs of which are used as inputs by the engine control logic. Additionally, engines are equipped with various sensors for health monitoring purposes and cockpit displays. These can include lubrication and fuel system sensors (pressure and flow), accelerometers, and gas-path instrumentation for performance monitoring purposes. Depending on the active control technology, advanced sensors may be required for special sensing tasks, reliability demands and harsh environment. Today, active applications are still limited by the gap between available sensor and actuator technologies and the operating environment in an aero engine.

Based on the provided input signal the controller reacts with a command signal for the actuator. Similar to the sensor, the actuator must be placed at a location where it is able to modify the current component state. As the control system fully relies on its functionality and authority, the actuator must be robust and reliable. This results in one of the challenges of active control: while increased functionality is obtained through the addition of complexity, the clear target is a net gain in reliability, brought about by the added complexity [2.9].

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.

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 (e.g. via forces or thermal heat) than

the net benefit, is not suitable for an active control system. The best actuation system follows the principle of small and smart. The weight of the actuator has to be minimized because an overall increase of the propulsion system weight would have a negative effect on aircraft fuel consumption.

In many cases the development of so-called non-linear actuation principles are strongly recommended. Examples are the direct influence of turbulent structures or the non-linear conversion of a frequency change into an amplitude change. But it must be recognized that such a development is just at the beginning.

One of the major obstacles for the technical realization is the link to a power source. The actuator and the processing unit (and in some cases also the sensor) require (electrical) power to operate. Both, an appropriate transmission path and a power source will be subject of future intensive research. The simplest way, a wired link for power and information transmission between a (central) electric source and an active control system, is not applicable in any case. Safety and design (e.g. wires through inflammable zones) reasons require much tailored solutions (e.g. wireless or infrared). While the transmission of information is relative easily realizable, the generation and (wireless) transmission of power is still an open question. Transmission solution based on magnetic or electric fields are most promising currently. The preferred solution is the power generation at the location of the power consumer (actuator, processing unit). An aero engine has the potential advantage to provide various energy sources at a very high level of energy density, e.g. local velocity, pressure or temperature gradients. However, the research on that field is relatively rare.

Beside the pure efficiency and operability increase, the new technologies have to fulfill all the airworthiness, safety and durability requirements known from today's engine generation. While the effectiveness of some technologies has already been shown in lab-scale demo tests, a huge effort in research and development has to be spent in the future to implement these technologies in engine rig and finally production engines.

In the following the advantages and limitations of passive control are discussed for each engine components. The benefits of active control technologies to further increase the operational flexibility and efficiency of each component will be reviewed, including highlighting the physical control processes and characterizing the sensor and actuator technology needs. The detailed sensor and actuator requirements in terms of operational environment (temperature and pressure), sensor capability (frequency, bandwidth, accuracy, resolution), and actuator capability (frequency, bandwidth, performance) will be summarized in a summary table in Section 2.3.

2.3 COMPONENT TECHNOLOGY

Today's aero engines consist of highly optimized components like inlet, compressor, combustion chamber, turbine and nozzle. The application of active control technologies provides the required next step for a further increase in operational flexibility and efficiency. The following chapter describes selected high pay-off technologies for the gas path components expected for the next engine generations.

2.3.1 Inlet

2.3.1.1 Active Inlet Control

The main purpose of an engine intake is to provide the first stage compressor stage nearly clean and undisturbed air. Two typical engine installation configurations are well established:

a) The engine intake is integrated into the engine nacelle

This configuration is typical for civil aircraft powered by jet engines. The most common configurations are the under-wing installation (large aircraft) or the tail-mounted installation (small aircraft, narrow body aircraft). The challenge for these configurations is the increased tolerance against cross wind which usually requires thicker intake lips. But a thicker intake lips generates significant higher aerodynamic losses and, consequently, higher SFC during cruise. While the selection of the thicker, more tolerant intake lip is dictated by the safety requirements, the increased SFC is a result of the design compromise. The application of active or deployable-on-command passive flow control mechanism enables the avoidance of the design antagonism. The nacelle/ intake is optimized for cruise conditions. During the critical flight conditions (cross-wind, take-off) the flow control devices are applied. This design philosophy makes great demands on the reliability of the flow control devices because they have to be "fail save". Ongoing investigations try to modify pure passive flow control devices (vortex generators) to become actively controlled and integrated into a control loop.

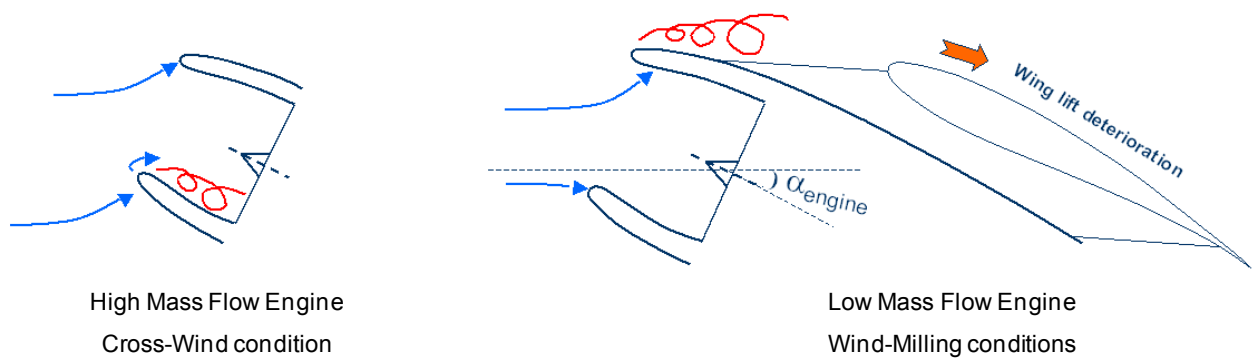

Figure 2.3: Flight Conditions Leading to Flow Separation in the Engine Inlet.

b) The engine is integrated into the aircraft frame

This configuration is typical for military aircrafts like fighters where the engine is completely embedded into the aircraft frame in order to reduce the aerodynamic losses and radar pattern of the airframe. Similar requirements were put on the design of UCAVs. The intake duct for these applications is formed as an S-shape duct connecting the intake opening in the airframe with the front stage of the installed engine in order to improve the stealth characteristic of the aircraft. A similar duct configuration can be found also at turboprop engines where the air intake is a small slot in the vicinity of the propeller spinner. In some applications the intake slot is places non-axis-symmetrical. The purpose of the S-shape intake duct is the reorganization of the air in order to provide the compressor an undisturbed axis-symmetric flow. The challenge for this type of configuration is the prevention of flow separation during the flow reorganization and turning during all flight conditions (take-off, cruise and climb) at a minimum of additional flow losses. Passive flow control devises in form of vortex generators are under investigations and realized in prototypes. The disadvantage of the passive devices is the permanent aerodynamic loss generation – also during flight condition when no flow control is needed.

c) Blended Wing Body Aircrafts

Blended wing body configurations for future aircrafts (civil as well as military) can be considered as a derivate of airframe with integrated engines. Most of the configurations under investigation use rear-mounted engines. In contrast to conventional engines where the engine face sees "clean" air conditions, the rear-

mounted engines are affected by the boundary layer of the whole blended wing. Various flight conditions change the wing boundary layer and, consequently, the engine intake conditions significant. Active flow control elements installed at the blended wing and/or the engine intake harmonize the flow conditions for the low pressure compressor. Therefore, active flow control becomes one of the major enabling technologies for this type of aircraft configurations.

In general, the active control of inlet flow distortions at the engine intake face (fan or low pressure compressor) can improve both the efficiency of the intake itself (by intake loss reduction) and level of flow conformity upstream of the compressor. The reduced flow distortion reduces the jeopardy of a stalled compressor and can be traded against higher compressor efficiency. Possible AFC devices are deployable vortex generators, pulsed micro jets or an active intake shape change.

The active management of the shock position at the intake can reduces the shock-induced losses (i.e. shock-induced flow separation) and the unwanted flow turning by shocks significantly, especially under off-design or crosswind conditions.

Detailed information on inlet flow control is given in references [2.11]-[2.14]

2.3.1.2 Active Noise Suppression

A number of concepts have been proposed to improve the acoustic effectiveness of acoustic treatment found in the inlet of commercial aircraft engines. Some of these techniques include actively modifying the porosity of the face sheet covering the honeycomb and therefore actively changing the acoustic characteristics of the cavities in the honeycomb [2.15]-[2.19].

2.3.1.3 Active Noise Cancellation

This technology generates noise in the aircraft engine inlet that cancels the noise generated by the fan. This technology works to reduce tones – that are characteristic of the noise generated by the rotor-stator interaction. The technology works to reduce noise, but the accompanying system (measurement devices, acoustics sources, and controllers) makes it difficult to package the device in a real system [2.20], [2.21].

2.3.2 Fan and Compressor

2.3.2.1 Component Requirements

The compression system is one of the key elements of the aircraft engine. An efficient thermodynamic cycle requires high overall pressure ratios at a minimum amount of loss. Turbomachinery losses occur due to friction losses, secondary flows, separations and shock losses. The leakages of air between rotating and stationary parts form another important source of losses. These can be found at airfoil tip gaps and internal seals. Modern state-of-the-art compressors reach polytropic efficiencies in the order of 90%.

The stable operation of the jet engine has to be assured throughout the operational envelope of the aircraft. For the compression system this results in the requirement of stall and surge free operation at any possible flow condition. Today's compressors are designed with an adequate surge margin to achieve this target. At the engineering stage surge margin stack-ups are used where different effects such as transient operating line excursion, inlet distortion and tip clearances are taken into account (SAE AIR 1419 rev. A). Typical surge margin requirements are shown in Table 2.1.

Table 2.1: Typical Surge Margin Requirements at ISA, SLS [2.22]

	Fan	LPC/IPC	HPC
Military fighter	15 – 20%	20 – 25%	25 – 30%
Commercial aircraft	10 – 15%	15 – 20%	20 – 25%

As the worst case has to be considered here, not all of the accounted effects are necessarily to occur during the entire mission of the engine. The surge margin requirement limits the exploitable performance of a compressor in terms of pressure ratio, efficiency, and engine dynamics.

The mechanical integrity and airworthiness of the compressor parts are very important requirements of the components. The harsh operating conditions together with the strict reliability requirements make it difficult to design compressor parts with enough life. The parts have to operate at high temperatures and at extensive rotational speeds. However, the component is optimized for a minimum mass which results in thin structures with high stress levels. These structures are susceptible to vibrations at different engine orders of the shaft speed. An additional requirement is given by loss-minimized aerodynamic shapes, which often contradict life demands.

2.3.2.2 Active Surge Control

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

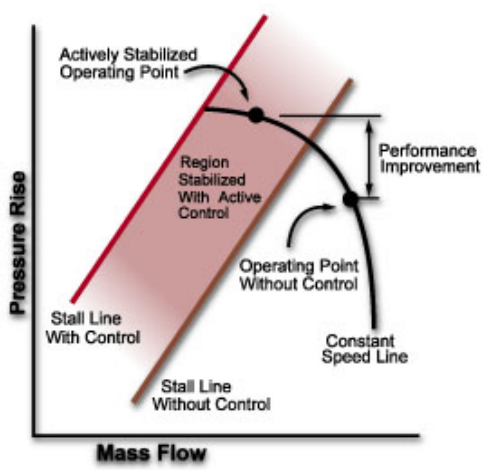

Figure 2.4: Enhanced Compressor Operating Point by Active Surge Control [2.23].

The general feasibility of surge control has been proven in different compressor and engine demonstrators. The basic principle goes back to the possibility of detecting the flow conditions close to the compressor stall point and counteracting by blowing, guide vane movement or de-throttling.

When approaching the stall point a compressor develops stall precursors: high frequency pressure and velocity fluctuations which can be measured by pressure probes or hot wire sensors. The fluctuations occur as modal waves or pressure spikes. The time between the measured precursor and the stall or surge event depends on the aerodynamic nature of the phenomenon. The time delay between the first occurrence of a stall precursor and the stall event is in the order of a few milliseconds. Therefore, it is very challenging to measure and react on a characteristic unsteady disturbance which leads to a compressor stall. Additionally, the kind of unsteady event is very dependent from the actual compressor design and not straightforward transferable for different compressor designs.

The 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 [2.24].

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 of 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 [2.25]-[2.28] as well as in complete engines [2.29]-[2.31]. The achieved benefit depends on the design of the injection system, the injection parameters and the control system which is used for the specific application [2.32]. An increase of surge margin in the range of 40% compared to a solid casing has been demonstrated.

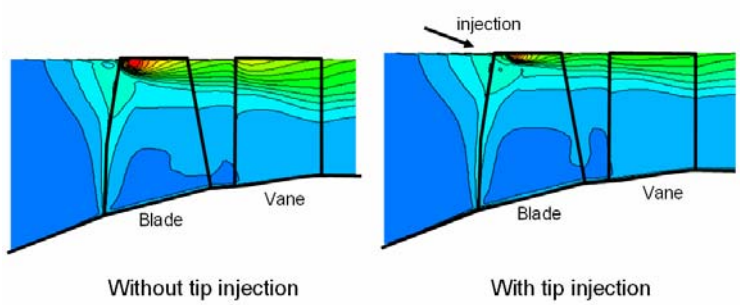

Figure 2.5: Entropy Contours Close to the Surge Point during Active Surge Control by Tip Injection.

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 traveling 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 [2.33], [2.34].

A third method uses fast actuating 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 behavior of the system. Specially designed controllers are able to operate the compressor in its conventionally instable regime [2.35], [2.36].

In spite of the technology's high potential no flight worthy system of an active surge control has been brought into service up to now.

2.3.2.3 Active Flow Control

Active flow control refers to a set of technologies that manipulate the flow of air and combustion gases deep within the confines of an engine to dynamically alter its performance during flight. By employing active flow control, designers can create engines that are significantly lighter, are more fuel efficient, and produce lower emissions. In addition, the operating range of an engine can be extended, yielding safer transportation systems. The realization of these future propulsion systems requires the collaborative development of many base technologies to achieve intelligent, embedded control at the engine locations where it will be most effective.

Some aerodynamic principles of flow control are already known since the 30s of the last century. However, the limitations in previous manufacturing technologies retard the application of some of flow control techniques in turbo machines. The better understanding in flow physics, the improved manufacturing technologies and the demand of efficiency and operability increase enforces the application of active flow control techniques.

Some of the presented technologies can be considered as passive or at least semi-active flow control techniques because they are changing the aerodynamic properties of engine subcomponents by their presence.

These technologies are well suited to improve the aerodynamics during off-design operation of a subcomponent but decrease aerodynamic performance during operation at design condition. A typical example of a pure passive flow control device is a boundary layer trap which forces the laminar-turbulent transition. This trap fulfills its purpose (transition) but generates a permanent loss. An intermediate step to reduce the permanent loss is the application of flow control technologies which are deployable when their effect is needed. Some of these technologies will be deployed in advance when the probability of an avoidable event (e.g. blade stall) is significant increased. This methodology may have an impact on the general performance of the engine. A better approach consists in a fully controlled application of flow control which is only deployed when needed. This methodology additionally requires the integration of a suitable sensor. The main advantage is the negligible impact on engine efficiency. However, the design of such a system requires more effort in R&D. A further improvement can be expected by the miniaturization of flow control devices. Their impact on the general properties of an engine (weight, efficiency) is further reduced.

The following section gives an overview of active flow control techniques.

a) Transpirated and aspirated compressor airfoil and annulus

The blades and platforms are equipped with rows of small holes through which air is ejected or sucked. 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.

b) Pulsed Jets

A special configuration of the method mentioned above 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 the zero-mass-flow devices (aka Synthetic Jets), on high speed micro valves (actuation frequency in the order of a few hundred Hertz, hole diameter in the order of a millimeter), on the bases of plasma jets (generated by high

voltage beam) or on micro-combustors where a small amount of fuel is burned inside a small cavity beneath the blade surface. All the pulsed jets are driven by an external energy source (i.e. electrical power) and can be, therefore, included in the engine control and management system.

c) Microjets

The benefit of micro-sized flow actuation devices is the small dimension which adds only little additional weight to the engine. Reliability and robustness has to be considered under the prospective of the engine service interval which is in the order of 20000 hours. The first applications of fluidic actuation devices are realistic for the low temperature engine components (e.g. intake, low and intermediate pressure compressor). The environmental temperature for the actuation device is between -50°C . . . 600°C, approximately. It is not necessary that a specific device design has to cover the complete temperature range, but the actuator technology should be applicable over the given temperature range. Depending on the flow phenomena to be influenced, the actuation devices need to cover different frequency spectra:

1) A flow phenomena which scales with the shaft speed (e.g. stalled blade passages) requires a device operating at about 200 Hz ... 300 Hz;
2) Flow phenomena like large flow separation at the blades (stalling blades) can be influenced by devices in the order of 500 Hz to few kHz;
3) A flow phenomena linked to the blade passing frequency requires a device operating at about 5 kHz ... 20 kHz; and
4) A flow phenomena scaled with the vortex shedding frequency (of a thin compressor blade) requires about 50 kHz ... 100 kHz.

The first two applications are the most likely scenarios for future generation of engines.

d) Application of the Coanda effect at the trailing edge of a blade

The Coanda effect has the capability to turn wall-bounded flow at very large angles around a circular trailing edge without flow separation. The method enables the design of blades with much higher turning during off-design conditions. However, the drawback is the thicker trailing edge compared to the standard airfoils which generates higher losses in general.

e) Airfoil Morphing

Airfoil shape change, especially in junction with Shape Memory Alloy (SMA), is another method to adapt the blade geometry according the aerodynamic requirements during the compressor operation. The incidence/ deviation angle of the flow increases/decreases as the compressor operates at lower mass flow rates than design conditions. If a blade is equipped with SMA (e.g. SMA wires embedded in a composite blade) the shape of the blade (e.g. chamber line) can be changed slightly by activating the SMA effect. The difficulty in applying this technology is the generation of the phase change temperature which initiates the shape memory alloy effect. The current available SMA material has a phase change temperature of about 100°C. In near future SMA material with phase change temperatures of about 500°C … 800°C can be expected.

f) Vortex Generator

The application of vortex generators which consists of a small piece of metal sheet mounted perpendicular (or inclined) to the component surface but inclined to the incoming flow is well known for wings and intakes.

The main disadvantage of the (passive) device can be seen in the permanent loss generation. The usage of deployable vortex generators reduces the losses significantly.

A key element of active flow control is the sensor technology. The mechanical, structural and operational requirements for sensors are very similar to the requirements of the active flow actuators. Both devices operate at similar conditions. The majority of state-of-the-art sensors used for engine monitoring focus on the measurement of (unsteady) pressure and temperature, rarely velocity. However, 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 (laser or infrared diodes) is advisable due to their non-destructive measurement principle. The development of advanced sensors can improve the prediction capability significantly, e.g. a shear stress sensor can identify a flow separation more reliable then a pressure sensor.

References [2.37]-[2.59] provide detailed background information on active flow control.

2.3.2.4 Active Clearance Control

Clearances represent one of the basic problems in turbomachinery as they have a negative impact on efficiency. In the compressor especially radial blade tip clearances have a detrimental effect on component performance and stability. Active clearance control (ACC) helps to maintain stability and efficiency by maintaining optimized radial clearances throughout the whole operating range of the compressor. In conventional design the thermal behavior of the compressor often is adapted by adding weight to the casing. Presently available systems are based on the thermal expansion of the casing, which can be controlled by modulating cooling air. The amount of cooling air is scheduled over an operating parameter, such as corrected speed or 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 tip clearance height a signal can be generated which is fed into an actuator. The actuator adjusts the position of the casing, modifying clearance to an optimum value. The actuator may be designed as a thermal, mechanical or pneumatic acting system [2.60]. The main advantages of advanced clearance control systems are given by the capability to react on any clearance change and thus counteracting deterioration and transient effects. This improves the component efficiency, not only for a new engine with lower incremental margins but also for a deteriorated engine by keeping optimum clearances over the engine life. The compressor is additionally improved by enhanced stability margin. By applying ACC the actively controlled components have a positive influence on fuel consumption, safety, reliability and maintenance cost.

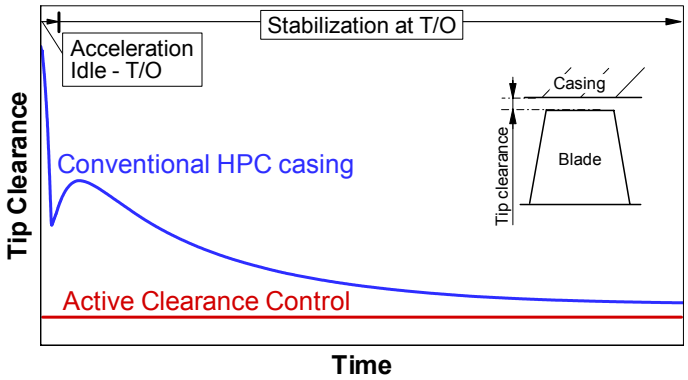

Figure 2.6: HPC Tip Clearance for an Acceleration Followed by a Stabilisation at High Power Setting.

Active Clearance Control (ACC) may be used in the compressor to enhance the aerodynamic stability. This can be achieved by a closed-loop system which adjusts the radial tip clearances to an optimum value and counteracts the transient movements of casing, blade and rotor. As clearances represent one of the critical issues mainly in the rear stages of the high pressure compressor, advanced clearance control systems will offer a large potential here. Clearance sensors should feature a robust design which withstands compressor pressures and temperatures. 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. An example of a closed-loop ACC system in a centrifugal compressor has been successfully demonstrated [2.61]. It is also possible to control compressor stability by the modification of local tip clearance using magnetic bearings [2.62].

2.3.2.5 Active Vibration Control

Both rotating (blades) and stationary (vanes) components of an aero engine have eigenfrequencies which (if resonant) lead to a reduced component life or an engine failure.

There are two solutions of such problems:

a) Design the component without critical eigenfrequencies in the operating range; and

b) Introduce damping devices that allow critical resonances in the operating range that, due to its amplitudes, do not lead to a HCF failure.

The first way often leads to heavier parts and aerodynamic design restrictions. Additionally, acoustic vibration produces a strong noise signature. The second alternative, the use of damping devices, overcomes above limitations but also means more complex systems. Active control systems may require additional electrical power placed on the rotating system. With time it may lead to the introduction of an electrical generator on the engine.

During the last 20 years passive damping systems have been successful developed. They represent the state of the art of mechanical damping devices, however they are mostly suitable to damp fundamental modes, for which they must be tuned (on weight and shape). One clear restriction on passive damping is that they are not able to adapt to changes in component vibration frequencies (e.g. geometrical deviations leading to vibrational changes). Hence, passive damping requires locations of damping devices where displacement is

big enough to be restrained by the damper. This restriction makes them unsuitable for small and high frequency vibration modes (e.g. chord-wise modes).

Active vibration control (AVC) could help to overcome design restrictions induced by resonant vibrations during the operating range. When applying AVC, vibrations within the operating range could be accepted and open new spaces for improved aerodynamic blade design concepts. The development of active damping systems allows damping devices to cope with small vibration amplitudes and expands the range of usability of damping devices. Active devices can be introduced as an additional part or even be integrally installed on the component, e.g. casted with airfoils.

The advantages of active damping systems are:

- Lower weight of the components because of less design restrictions;
- Acceptance of critical resonance within operating range, that leads amongst others to more effective aerodynamic design that produces resonant profiles;
- Noise reduction; and
- Reduction of damage during stall condition.

The following disadvantages arise:

- A current generator is necessary; and
- Additional electronics create more complex systems, which leads to lower reliability.

One promising active damping line is the use of piezoelectric elements or other material/physical phenomena that dissipate energy. These elements transform the mechanical energy in electrical energy, so attenuating the vibratory amplitude. The approach has been successfully developed for aeronautic structures (wings), however its application in an engine is not possible yet due to restrictions in operating temperature and pressure/deformation range.

Due to the better availability and the increased capacity of electrical power of the next generation aero engine (so-called “more electric engine”) some advanced design concepts to improve the rotor dynamical behavior of aero engines are studied now again. Different level complexity – from pure passive to full authorized systems – is considered with the strong focus on aero engines (see references [2.63]-[2.73]).

2.3.3 Combustor

2.3.3.1 Introduction

Active combustion instability control (AIC) manipulates combustion behavior using a dynamic hardware component (actuator) that rapidly modifies an input into the combustion process. In closed-loop control a sensor is monitoring the combustor output in real time to determine actuator action via control algorithms. Adaptive control refers to a self-adjusting controller that can modify the controller action depending on the transient external circumstances.

Initial AIC combustor experiments were motivated to control combustion instabilities in aero engine augmenters. More recently the instability control has been focused on very-low emissions stationary gas turbines and will become critical for future aero engines with operation near lean blow-out limits. AIC is also being explored for reducing non-uniformities of turbine entrance temperature distribution (reduce pattern

factor). AIC generally focuses on combustion dynamics with high-band width actuation, typical in the l00Hz to 400Hz frequency range.

AIC is an attractive approach because it relies on proper timing of fuel injection rather than on spatial, geometric changes as required in passive approaches. Since timing adjustment is simpler than the precision geometric modifications associated with passive control (often late during the combustor design), AIC can provide flexibility and elimination of costly design changes. Also for future combustor demands, customary methods of design changes may be approaching their limits, in particular for aero engines because compact design, transient operation, and wide operating range. Challenges for implementation of AIC include increased complexity, development of reliable sensors and actuators for harsh environment operation and of robust controller, and challenge of adding and embedding AIC components.

The following sections will briefly discuss:

1) Physics of control processes;
2) Review of recent AIC activities;
3) Status AIC control components; and
4) Specific requirements for actuators and sensors.

For additional details the reader is referred to several AIC review papers [2.74]-[2.84].

2.3.3.2 Physics of Control Processes

Combustion instabilities result from thermo-acoustics through the coupling of unsteady heat release (from oscillations of local fuel/air ratios) and acoustic oscillations at high frequency (greater than 1 kHz) and low frequency (100 to 1000 Hz). Lean flames, which are of interest for very-low emissions combustors, have a particular high susceptibility for thermo-acoustics. Since high-frequency oscillations can be successfully controlled by passive means (for example damping resonators), active control focuses on low-frequency oscillations.

The local oscillations of the fuel/air ratios can be caused by several mechanisms, including unsteady flow structures, vortex/flame interactions, flame/boundary interactions, coupling between pressure oscillations and the instantaneous flame position and shape, fuel line/air feeding perturbations, and other processes. Active control in realistic combustors has predominantly utilized out-of-phase fuel injection to suppress the instability. In laboratory tests, other methods, for example control of vortex dynamics as control of temperature fluctuations, is being explored and may optimize active control authority and efficiency.

Pollution Emission. The lowest level of NOx emissions for gas turbines can be achieved by employing lean combustion strategy at low flame temperature. However, as the fuel-air ratio approaches the lean blow-out (LBO) limit, the flame temperature will not support sufficiently fast CO oxidation rates and its concentration in the combustor exhaust increases. There is a “window” of fuel/air ratio, and of corresponding flame temperature, that will simultaneously result in low NOx and CO. However thermo-acoustic instabilities in these regimes are a common development challenge.

Pattern Factor. With a non-uniform fuel/air ratio distribution hot-streaks exist in the combustor exit plane entering the turbine. These hot streaks limit the operating temperature at the turbine inlet and thus constrain performance and efficiency. Elimination of hot streaks provides greater turbine life, effectively increases

maximum operating temperature and increases engine efficiency and performance, and also contributes to emission reduction.

2.3.3.3 State-of-the-Art of Active Combustion Control

Laboratory Tests. Recent gas turbine research investigated the role of large-scale flow structures in driving gas turbine pressure oscillations and the use of precursors for identifying and controlling LBO.

Active control of fine-scale and large-scale mixing and associated combustion processes has been used in flames and dump combustors to suppress combustion instabilities, optimize fuel/air mixing, extend LBO limits, and enhance combustion efficiency with simultaneous reduction of soot, CO, and NOx emissions [2.85]. This research was extended to swirl stabilized combustion [2.86],[2.87]. Instability of axisymmetric and helical unstable modes was suppressed by reducing coherence of the vortical structures. In multi-swirl stabilized combustor, simultaneous measurements of acoustic pressure, local OH radical emissions and phase-resolved OH chemiluminescence imaging showed that pulsation of the flame front during unstable combustion is associated with evolution of large-scale structures. These results show the important role of fluid dynamics in driving oscillations in gas turbines, which may lead to improved control authority of actuators on the combustion process.

To extend the operational envelop, lean flame blow-out was detected and actively prevented in a premixed, swirl stabilized combustor. The control system maintained stable combustion (and low NOx) at lower equivalence ratio by redirecting a fraction of total fuel to central premixed pilot [2.88]. Additional insight into the dynamics of the blow-out phenomenon was provided using simultaneous local OH chemiluminescence data and high speed visualization. The work was extended to monitoring the proximity to blow-out with the flame's ion signature in addition to the acoustic emission [2.89].

Despite the success of AIC implementing in surface power gas turbines, challenges remain for AIC implementation in aero-engines. These challenges include development of light and reliable actuators, efficient and safe control authority of the actuators on the combustion process, and robust control algorithm. Additional details will be discussed in the following section on AIC Control Components.

Combustor Tests. The confidence and awareness in AIC as enabling technology has significantly increased with full-scale aero-engine tests and power gas turbines field operation for over 19,000 hours.

AIC was successfully applied to the Siemens heavy-duty power gas turbines with base-load power output up to 250 MW [2.90] [2.91]. Instabilities of azimuthal modes up to 290 Hz were suppressed using pulsed gaseous pilot fuel modulation. The suppression was achieved at premixed and diffusion-based operations at intermediate load levels, during switchover processes, and also at base-load levels, allowing for 5% load increase.

Rolls-Royce has demonstrated control of aero-engine afterburner rumble at 120 Hz as far back as the early 90s, although the results were not made public until 2000 [2.92]. With direct injection of pulsed secondary liquid fuel combustion instabilities of the RB 199 engine were suppressed. A simple time delay controller was used in the full-scale demonstrations.

A practical AIC system for mitigation of combustion instabilities in a lean, premixed single-nozzle combustor was demonstrated by United Technologies Research Center (UTRC) at realistic operating conditions [2.93]. A full-scale engine fuel nozzle of 4 MW power output was modified to incorporate a simple liquid fuel flow

actuator. The system was capable of reducing pressure oscillations near the LBO limit, while maintaining or reducing NOx and CO emission levels. Simple phase-shifting algorithm and more complex adaptive algorithms were developed.

A single-nozzle combustor, which replicated longitudinal combustion instabilities in an aero engine, was also used by NASA [2.94]. Two adaptive control algorithms were developed. The first involves fuel modulation with a control phase that continuously slides back and forth within the stable region. The second control algorithm combines wavelet like analysis and an observer to predict states of instabilities. The control approaches were successfully evaluated against a simplified simulation of combustion instability, a more physics-based model, and in the combustor rig [2.95].

High-band width AIC will be most likely integrated with low-band width AIC using fuel scheduling to avoid acoustics and LBO [2.96] and to reduce pattern factor [2.80].

2.3.3.4 AIC Control Components

Dynamic Models. Advanced design and analysis tools such as the National Combustion Code and physics-based combustion dynamics models can guide the design and development process for modern low-emission gas turbine combustors. However, dynamic modeling is not as mature as steady-state CFD modeling. This limits the use of dynamic models during the design phase. NASA has developed a 1 D model that exhibits self-excited thermo-acoustic oscillations in premixed combustor. Simulation closely matched the rig data in oscillation amplitude, frequencies, and operating points at which instabilities occurred [2.97].

Sensors with the proper time-response characteristics are needed in closed-loop feedback control applications. The main issues are low cost and reliable operation in high temperature and vibration environments.

Conventional sensors typically include piezoresistive-type or piezoelectric-type transducers for pressure measurements, and photodiodes and photomultipliers to provide information on chemiluminescence and heat release. Diode laser for monitoring performance (CO emission) and vortex characteristics (combustion temperature fluctuations) for closed-loop active control have been demonstrated [2.98] and have been proposed for a gas turbine health monitoring system [2.99]. MEMS based sensors, which allow several advantages, including miniaturization, redundancy, low mass, high reliability, low energy consumption, and low cost per provided data, are becoming available at a fast pace. Current sensors provide global and line-of-sight information. Future sensors, which would determine localized conditions, will benefit active control (for example local flame blow-out sensors and local fuel/air ration sensors).

Actuators. In any practical application, actuators are the key components that enable the use of the active control approach. Fluid dynamics and combustion responses to excitation are the single most important characteristics that determine the potential and success of active control. In addition to increasing the actuation authority, low weight and high reliability during operation in harsh environment are critical.

Siemens used a direct drive valve (DDV) for **gaseous** pilot fuel modulation, which was specifically developed by Moog Germany.

Challenges remain for scale-up with **liquid** fuel modulation, where time delays increase with liquid fuel atomization, droplet heating, vaporization, and combustion. The current actuator limits in amplitude, rate, and bandwidth will become even more severe in future applications as AIC requirements move to higher frequencies.

For the NASA single-nozzle combustion rig, Georgia Tech has developed a magnetostrictive actuator that is connected to a pintle-type injector [2.100]. Other AIC actuators that have been previously reviewed include:

1) Compression drivers that add acoustic energy at particular frequencies;
2) Flow injectors that add secondary mass flux at a particular timing;
3) Mechanical devices, piezoelectric actuators, and pulsed air jets that either trip the transient boundary layers or change the shear layer mixing;
4) Pulsed-combustion actuators that generate periodic heat release and sound waves; and
5) Moving surfaces that create local disturbances.

Recently Georgia Tech has developed a "smart" liquid fuel injector for active control by controlling spray pattern by controlling flow rates of two coaxial counter-swirling air streams [2.101].

With the inherent frequency limit of electromechanical actuation, new approaches should be explored, such as MEMS technology for highly distributed flow control and fuel actuation. Also emerging actuator materials, such as improved shape memory alloys, electromagnetic material, morphing material, other should be researched.

Control Algorithm. For actively controlling combustion through the use of a feedback loop, a number of different control approaches have been implemented over the years. For controlling the actuation timing and duration based on real-time sensing, some knowledge of the particular system response to given actuation is required. This is generally acquired through a process called system identification, either through experimental transfer functions or model-based approaches.

The traditional approaches that required on-line system identification include proportional control (which is typically based on time- or phase delay), neural network control (which can be pre-trained using simulation data or direct experiments), and fuzzy logic control (which is similar to neural networks except the actual sensor nodes in neural networks are replaced by fuzzy functions and fuzzy rules).

Model-based control describes a wide variety of adaptive control approaches with physically based models, which are either reduced-order models or simulations of system acoustics, flow dynamics, reaction dynamics, actuators and sensors, and their coupling. These models are being developed with a goal to reduce the need for the experimental system-identification procedure.

UTRC [2.102] developed a control algorithm that connects a reduced-order model of the combustion dynamics with control theory. The model, using linear and nonlinear frequency domain descriptions, is used to determine fundamental performance limits of the controlled systems related to actuator bandwidth, saturation, and delay, robustness of the controller in the presence of uncertainties, sensitivity to noise in practical systems, and effect of damping. NASA developed control algorithms have been described earlier.

2.3.4 Turbine

2.3.4.1 Component Requirements

Modern aero engine turbines are designed and optimized with respect to several main targets. As turbine efficiency has a strong impact on the thermodynamic cycle, the component efficiency plays an important role for the optimization of fuel burn and CO_2 emissions (see Figure 2.7). The weight of a jet engine is also directly

related to fuel burn, causing the need for a light weight design. As a consequence, the work done by the turbine is maximized while the stages and parts count is minimized, resulting in a high aerodynamic loading level. This is characterized by large flow turning angles and high pressure gradients. Separation bubbles occur on the airfoil surfaces causing losses and limiting the design space. This is especially compromising the performance at high flight altitude due to low Reynolds numbers. Additionally, these features cause strong three dimensional flow effects within the turbine blade passage. Consequently, strong secondary flows occur, which further reduce efficiency. Current technology uses advanced 3D aerodynamic design with features like endwall contouring and high lift airfoils [2.103]. Another important source of losses is the tip clearances. Overtip leakage does not contribute to turbine work and causes strong vortices at the blade tips.

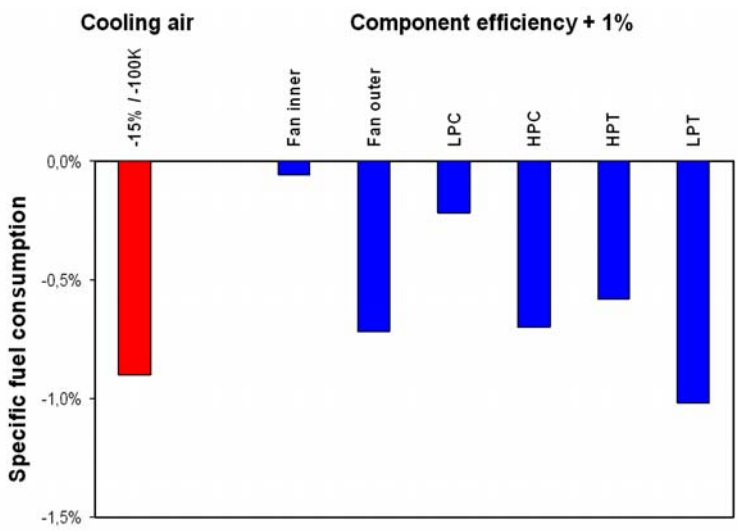

Figure 2.7: Typical Exchange Rates on Fuel Consumption in a Two-Spool Turbofan Engine [2.104].

As the cycle efficiency increases with temperature, the trend in modern gas turbines goes towards very high turbine inlet temperatures. Current inlet temperatures are beyond tolerable material temperatures, so strong cooling is required. If the cooling flow is injected behind the first stator vane throat, it will reduce the cycle efficiency to a large extent. Turbine capacity is another important parameter for engine operation, as it limits the flow through the gas turbine and controls the compressor working line.

An important environmental issue is the noise emission which has a large influence on aerodynamic turbine design. Finally the production and maintenance cost of a turbine has a significant impact on the economics of the aero engine.

2.3.4.2 Active Clearance Control

The radial gap between the casing and the rotating parts of a turbine (i.e. blade tips or shroud) causes aerodynamic losses which negatively affect gas turbine performance. Opening this gap yields a decrease in turbine efficiency leading to an increase in thrust specific fuel consumption TSFC. Tip clearance varies with rotor speed due to centrifugal forces and gas conditions such as temperature and pressure. Within a flight mission an engine faces different ambient conditions and operating points, along with large variations in tip clearances. In addition, tip clearance changes during transient maneuvers due to the thermal behavior of the

turbine components rotor, blades and casing. During an acceleration, for example, the rotor speed increases leading to a closure of tip clearance. The gas temperature increases and heats up the turbine components, whereas the blades heat up quickly due to their low mass and full contact to the gas. The casing heats up much slower than the blades and increases tip clearance. The rotor disks heat up even slower than the casing due to their high mass and the lower temperature of the surrounding internal air system, see Figure 2.6. The condition of least tip clearance within a flight mission is called "pinch point". The difference in thermal behavior of the components leads to tip clearance variations with time even after the demanded rotor speed has been reached. With respect to a safe engine operation, the cold build clearance is designed for minimized tip clearances on one hand, but also for rub avoidance between blades and the casing in all situations within a mission. However, every operating point besides the pinch point features a larger clearance and therefore lower efficiency. Passive clearance control systems modify thermal behavior with different materials, insulation techniques, etc., but these devices are not capable of compensating clearance variations due to speed changes. In order to minimize tip clearance during different operating conditions, active clearance control (ACC) should be incorporated.

Most modern engines feature a thermal turbine ACC-system, which is state of the art technology. By applying cooling air onto the supporting structure of the turbine the radial position of the casing can be modified in order to minimize tip clearance by thermal expansion. This technology's benefit is mostly exploited during cruise operation for commercial aircraft. However, thermal ACC-systems are relatively slow, so they cannot react to quick speed changes, which must be considered in the amount of cooling air supplied onto the casing. Provision of additional clearance is necessary to allow engine acceleration without rub-in.

A possibility to overcome the delay of the casing adjustment is to position it mechanically rather than thermally. NASA has investigated different mechanical actuation systems for the high pressure turbine in its UEET program [2.105]. Most sophisticated concepts for a mechanical ACC system use electrical or hydraulical actuation mechanisms with mechanical transmission. Other actuation concepts based on piezo-electric movement or shape memory alloys are promising but need further development. As all active systems, an active clearance control requires energy in terms of cooling air (thermal ACC), electrical or hydraulical power (mechanical ACC). This effort partly compensates the benefit gained through improved turbine efficiency, regardless of which actuation concept is used. A convincing balance of TSFC improvements (fuel costs, environmental issues) and maintenance costs due to improved complexity must be obtained to justify the effort of an ACC.

Today's engines mostly use an open-loop control scheme with a thermal ACC system. Dependent on spool speed, ambient condition, etc., the amount of air supplied to the turbine is scheduled. These open-loop control laws are only suitable for steady-state operation. During transient operation, special control laws need to overrule the prescribed valve schedule until steady-state condition is re-obtained. An improvement to these open-loop controls are model based control schemes. A tip clearance model within the engine control unit provides feedback by constantly calculating actual tip clearance dependant on performance parameters. Based on this signal the ACC actuator is set to minimize tip clearance for steady-state or transient operation. Nevertheless, neither an open-loop nor a model based control scheme are capable of compensating tip clearance growth due to deterioration. Closed-loop control laws incorporate a tip clearance sensor, giving a signal to the control unit, based on which the ACC actuator adapts its position. In principle, such closed-loop controls can detect any kind of clearance variation (symmetric, asymmetric, deterioration) and react quickly (if in use with a mechanical actuation system) [2.106]. However, turbine tip clearance sensors have to meet high demands on accuracy and must operate successfully in a high temperature, high vibration environment with contaminated air [2.107]. There is currently no turbine tip clearance sensor being used on engines in commercial service.

A rule-of-thumb equates a 0.25mm reduction in turbine tip clearance to a reduction in engine exhaust gas temperature (EGT) of up to 10°C and an increase in turbine efficiency of up to 1%. The result would be a reduction in SFC by as much as 1% with a proportional reduction in emissions. This reduction could save a total of $160M+ per year in fuel costs for the current civil aircraft fleet and the corresponding emission reduction would result in benefits to the public at large [2.108].

2.3.4.3 Cooling Air Control

Structures in the hot section of a gas turbine need to be cooled by air flows to provide sufficient durability. As cooling air flows represent a loss for the thermodynamic cycle, their amount needs to be optimized. Three approaches for active cooling air control can be envisioned.

a) Film Cooling

Film-cooling of gas turbine vanes is the current approach to maintaining turbine durability in the hot engine environment. The effectiveness of this approach depends on the extent to which the cool jet-fluid adheres to the cooled component surface. Lift-off of the cooling jet flow or other mechanisms promoting mixing, cause loss of cooling effectiveness as they allow the hot "free-stream" fluid to come in contact with the component surface. The cooling effectiveness can be improved by actively controlling the jet flow in a manner such as to prevent/delay lift-off and suppress mixing. Furthermore, an actively controlled film-cooling system coupled with appropriate sensory input (e.g. temperature or heat flux) can adapt to spatial and temporal variations of the hot gas path. Thus it is conceivable that the efficiency of film-cooling systems can be further improved by intelligently directing the flow where it is most needed. Systems analysis studies have shown that a 4% reduction in cooling flow can improve specific fuel consumption by about 0.45%. Because of the small passages for the flow, it is envisioned that MEMS (Micro Electro-Mechanical Systems) technology will be critical to develop the enabling actuation system for active control of turbine film-cooling [2.109].

b) Cooling Air Modulation

The optimization of the amount of cooling air to the requirement of the specific operating point offers the opportunity to reduce mission fuel burn. Since gas turbine engines are designed for one operation condition (take-off, cruise), their thermal efficiency usually decreases for part load conditions. Usually the gas turbine is designed with a cooling flow rate for most extreme condition. The ratio between coolant flow and compressor inlet air flow is almost constant for all operation conditions, though the blade temperatures decrease due to decreasing turbine temperature for part load. Thus the blades are overcooled what leads to reduced efficiency as a part of the coolant flow does not contribute to turbine work. Typical commercial aero engines have exchange rates of 0,5% to 0,7% SFC reduction for 1% reduction of cooling air.

One way to overcome this penalty is the adjustment of the cooling flow to the required amount. Potential solutions aim at a control of the turbine blade cooling flow supplied by the compressor. An ideal modulation would allow a constant blade temperature with decreasing gaspath temperature until blade and gas temperatures are equal.

Numerical simulations of a modulated cooling air flow achieve lower turbine inlet temperature, lower SFC and higher compressor and turbine efficiency at an equivalent power level at all part load conditions compared to conventional engines [2.110]. Compressor efficiency could be improved by up to 1,5%. The enhancement obtained by coolant modulation is more eminent for high-performance engines because of larger amounts of cooling flow due to high turbine inlet temperatures. Another example [2.111] simulates a 50% cooling flow reduction during cruise. Together with a design optimization the specific fuel consumption could be reduced by 0,5%.

c) Cooling Air Cooling

For state of the art core engines about 20 to 30% of the air delivered by the HPC is used for cooling the HPT, thus "bypassing" the cycle and having further detrimental effects on the core. In current engines in service the cooling air flow path is fixed and the cooling air is "hot" compressor discharge air. If the supplied air flow is cooled by a heat exchanger, see Figure 2.8, colder turbine metal temperatures can be achieved. In consequence, the amount of cooling air can be reduced or the turbine inlet temperature increased. Both directions lead to an improved gas turbine cycle.

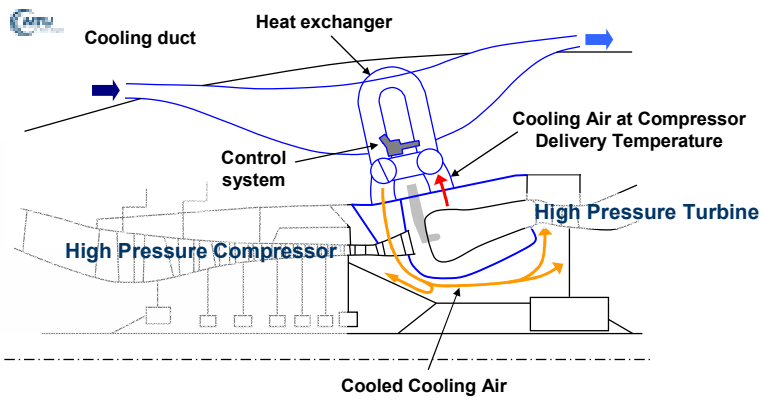

Figure 2.8: Gas Turbine Configuration with Cooling Air Cooling.

Cooling air cooling has been identified in US technology studies (IHPTET, VAATE) as an enabler for high pressure cycles with high turbine exit temperatures. But also for medium OPR cycles the potential is significant, as the necessary amount of cooling air can be decreased. Known studies provide cooled cooling air to the turbine blades, while the amount and temperature of the cooled air is fixed. Advanced systems supply cooled cooling air also to the stator vanes, the rotor disk and the liners in the turbine. The cooling air mass flow rate and temperature are actively controlled depending on the operating point. The technology offers the possibility to reduce the cooling air requirement to a minimum along with beneficial effects for engine design.

2.3.4.4 Active Flow Control

Comparably to the compressor, the fluid flow through the turbine can be modified by active means. These include fluid injection to energize the local flow, or suction to remove low momentum fluid. Typically flow control can be applied at potential separations on the airfoils surface, at the endwall region or as a method to improve the tip gap flow. In most cases, active flow control is used with modulated actuation at high frequencies to minimize the necessary energy input. Steady blowing or suction is also applied, but the required flow reduces overall efficiency which has to be traded against the potential benefit. Turbine flow control is able to prevent local separations, modify secondary flow structures and improve cooling effectiveness. Thus active control may contribute to high efficiency and low fuel consumption.

As an example, the secondary flow in the high pressure turbine may be improved by blowing jets out of small slots in the blade surface in the endwall region [2.112]. All injections yield appreciable suppression of corner separation and provide a significant reduction of total pressure loss with small injection flow rates.

A typical control strategy to prevent airfoil separations consists in using localized fluid injection [2.113]. An inclined plane wall jet, located upstream of the expected suction surface separation point, is used to suppress the separation. The wall jet supplies energy to the decelerating boundary layer downstream of the suction peak and increases the momentum in the near-wall region of the boundary layer. That in turn is expected to resist stronger pressure gradients and may delay or even suppress separation.

Another approach to separation control in a LPT turbine uses plasma actuators [2.114]. The actuators consist of electrode pairs separated by a thin dielectric insulator that is located on blade surface. High ac voltage produces an electric field which causes the air to ionize and induces a velocity component. Both steady and unsteady actuation were found to effectively control any separation.

The intermediate duct also promises opportunities for the application of flow control. In multi-spool jet engines, the low-pressure (LP) system has a much lower rotational speed and larger radius than the high-pressure (HP) core system. Hence, intermediate S-shaped transition ducts are needed to connect the high-radius LP system with the low-radius HP system. These annular ducts often carry loads, support bearings and have thick structural struts passing through them, making them large, heavy and expensive. Transition-ducts have become an important element to meet performance and weight targets. Due to the increasing flow area between the HP turbine and the LP turbine the fluid decelerates and the duct acts as a diffuser. As adverse pressure gradients can cause the boundary layer to separate the possible design space is limited. The application of flow control in the critical areas allows high diffusion factors while preventing any compromising separations [2.115], [2.116]. As a consequence, the duct produces lower pressure losses and the following turbine operates at higher efficiency. Current activities like the European research program AIDA (Aggressive Intermediate Duct Aerodynamics for Competitive and Environmentally Friendly Jet Engines) demonstrate promising results.

2.3.4.5 Variable Turbine Capacity

The loss of performance of a gas turbine at off design conditions is primarily caused by a component matching outside of the optimum. In order to keep engine performance at a constant level even under changing operating conditions, adequate re-matching of the engine cycle and improved internal matching of a component is of major importance. Therefore, active methods to control the engine operating point are of great interest. One possible candidate technology is a turbine with variable capacity. The capacity variation is typically accomplished by a rotation of the stator vanes of typically +/-10° increasing or reducing the effective throat area.

An actively controlled turbine can keep the turbine inlet temperature at a constant level. This provides significant savings in fuel consumption during reduced power demand. As the power output of the gas turbine is related to engine mass flow and turbine inlet temperature, the maximum power capability may be improved by a variable turbine. The change in the relationship between rotational speed and flow can also improve the transient engine response. Due to the fact that the turbine throat area controls the compressor working line the combination of variable geometry turbine and compressor can be effectively used to avoid stall and surge.

Existing variable turbine solutions can be found in land and naval vehicles as well as in power generation plants. As an application to aircraft propulsion systems is currently out of sight, this technology will not be further discussed in this report. The reader is referred to references [2.117]-[2.121] for further information.

2.3.5 Nozzle

2.3.5.1 Active Noise Control

The reduction of aircraft noise continues to be the subject of considerable effort. Active noise reduction has been a popular area of technology development the last couple of years. Much of the effort has been on advancing

noise reduction technologies where they can be turned on and off or even change geometries. The reason for this is that the noise reduction technologies almost always result in some loss of performance to the aircraft engine. If technologies can be developed that can be turned off when noise reduction is not needed, then there could be a system benefit to the aircraft. Some of the specific technologies that have been under investigation are described in the following.

a) Variable geometry chevron nozzles

One of the noise reduction options currently considered is the serrated nozzle, also known as the chevron nozzle. Some noise is generated by the shear which occurs between air streams traveling at different speeds. Lobed mixers which were used in the 1960's gave good noise reduction, but also produced a massive performance and fuel burn penalty. The trend towards higher bypass turbofan engines which has continued since then has made dramatic improvements by reducing the velocities of the jets, but ever increasing requirements for noise reduction has encouraged further investigation into methods of reducing the shear. The serrated nozzle is a more subtle approach which aims for more rapid mixing of the two flows to reduce this noise source. Flight testing (Figure 2.9) demonstrated the effectiveness of serrations for noise reduction, but also confirmed the expected performance penalty.

Figure 2.9: Flight Testing of Fixed Serrated Nozzle [2.127].

Since noise reduction is only needed at very low altitude, work has been ongoing to implement shape memory alloy materials (SMA) in chevron nozzle 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, see Figure 2.10. 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.

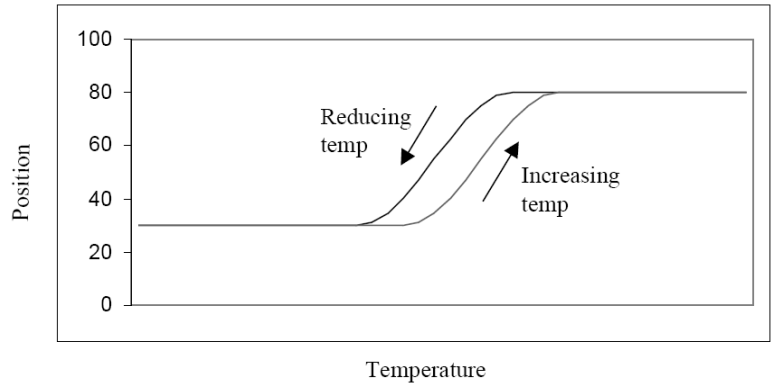

Figure 2.10: Position/Shape Control by SMAs [2.126].

SMAs have a very high energy output per unit weight, so should not cause a significant weight penalty. The disadvantages of slow actuation and low efficiency which may preclude them from other applications are not significant. Operation by heat could be an issue. Initial studies considered the use of ambient heating. Air temperature naturally reduces with increasing altitude. A unique SMA operating temperature range has been identified where completely autonomous serrations activated by ambient temperature would be deployed for take off and retracted at cruise. Concerns over the operational implications of the uncertainty of the exact altitude when withdrawal would occur have led to the consideration of applied heating. Warm air ducted from the engine to heat them during takeoff and early climb is likely to be the preferred method. Electrical heating is also under consideration. The primary challenge was to produce an SMA based system which would be capable of providing sufficient operational stiffness and high movement whilst still being cost effective and safe [2.122]-[2.127].

b) Fluidic Injection

Fluidic injection started as a way to avoid mechanical chevrons and get the same fluid dynamic effect with injected flow. Again, this has the advantage that it can be turned off when not needed [2.128], [2.129].

2.3.5.2 Adaptive Nozzles

Beside the application of "flexible" nozzles for military engines to obtain cycle adoption for different operation conditions and thrust vectoring, increasing attention is paid for adaptive nozzles for high-bypass civil engines. They provide some promising advantages:

- Adaptive nozzles allow for different operation conditions of the mixer during take-off (optimized regarding noise) and cruise (optimized regarding efficiency);
- Active surge margin control by adapting nozzle area; and
- The signature of an engine can be reduced by the use of a controlled exhaust nozzle.

The concept for an adaptive nozzle is to change the nozzle shape in response to bypass air temperature. An area change of only 4% would give significant benefits in performance and fan surge margin. It can also be applied for noise considerations.

Initial indications are that for the fan nozzle, ambient or bypass air temperature will be suitable as the control input. This will act directly on the SMA to cause it to change between the two stable positions. Using currently

available alloys, the core nozzle will require ducted air cooling to prevent damage. The preferred design uses two opposing, pre-stressed beam elements. A base material such as titanium forms a serration shape which is pre-bent to near the withdrawn position. The SMA elements pull the titanium into the deployed position. When hot, the modulus of the SMA is sufficient to hold this deployed position. Upon cooling, as altitude is reached, the SMA softens rapidly over a small temperature change to allow the titanium element to withdraw the serrations. Superficially, the serration element in this simple installation will resemble a bi-metal strip, the operation is however quite different, with a rapid change between two set positions. The advantages of space, weight and complexity are obvious [2.126].

2.3.5.3 Thrust Vectoring

The replacement of the current mechanical systems (one fielded in the PW F119 for the F-22 Raptor and a prototype demonstrator of a fully 3D mechanical vector nozzle for the EJ200 engine for the Typhoon Eurofighter [2.130]) with a fluidic approach has various potential benefits, as weight reduction and reliability advantages. Fluidic vectoring is already in use today in rocket engines.

Computational and reduced scale experimental studies jointly performed by airframe and engine manufacturers [2.130]-[2.133] have demonstrated the potential of fluidic actuation in throat area control of the nozzles of afterburning engines and also for thrust vector control either for enhanced agility of combat aircraft or in future unmanned vehicles to potentially reduce the need for moving aerodynamic control surfaces.

By fluidic skewing of the nozzle throat effective thrust vectoring can be accomplished. However the amount of air flow to control flow direction is in the order of magnitude 1% of injected flow for every 1.5 degrees of vector angle [2.133], which would have to be considered in the overall performance cycle of the engine.

2.3.5.4 Active Core Exhaust Control

Reduction of the exhaust plume temperature of the engine core is desirable for military transport aircraft both during engine-running ground operation and also in-flight to achieve IR signature reduction [2.134]. This can be achieved by a pulsed injection system integrated in the core nozzle that intentionally destabilizes the core-exhaust plume and thus causes a significant increase of mixing between the core exhaust flow and the surrounding air. By integrating the fluidic actuation system into a specially shaped plug nozzle, which is designed to reduce line-of-sight blockage to the hot turbine components a very effective system for temperature management of the exhaust plume is available [2.135], [2.136].

2.3.5.5 Afterburner Stability Control

It is well known that current augmented military jet engines have the potential problem of instabilities of the exhaust jet during afterburner operation. Basically there are two forms of instability:

- Axial, low frequency (buzz, rumble); without countermeasures risk of extremely high dynamic forces on low pressure rotor that might lead to catastrophic damage; and
- Radial, high frequency (screech); might lead to destruction of heat shields used for protection of the jet pipe walls and actuators due to overheating.

The existing stability control systems monitor certain frequency bands of the dynamic pressure (<100 Hz for longitudinal instability, > 500 Hz for radial instability).

In case of identification of one of the effects described above, current practice is to cut afterburner fuel flow and to actuate (open) the nozzle. The existing identification methods have to be improved in order to avoid false alarms. More intelligent sensors could improve the effectiveness of incident detection. Alternatives to piezo-electric sensors have to be investigated. Suppression of instabilities by active control using pulsed fuel injection has been discussed in Section 2.3.3.3.

2.4 SENSOR AND ACTUATOR REQUIREMENTS

As a general design rule, any active element used in a control scheme should be small, lightweight, robust, reliable and affordable. Installed in an aircraft engine, they have to withstand extreme temperatures, pressures and special operational constraints. The following table gives an overview on the gas path conditions in the engine. Starting conditions are not considered here.

Table 2.2: GTE Operating Environment

Operating Environment							
	Inlet	Compressor		Com-bustor	Turbine		Nozzle
		LPC	HPC		HPT	LPT	
Pressure [kPa]	15 – 105	15 – 300	30 – 1800	300 – 4000		100 – 1000	20 – 200
Temperature [°C]	-60 – 55	-60 – 150	0 – 700	700 – 1700		400 – 1000	300 – 500 >1800 (reheat)

The following operational constraints should be considered for sensors and actuators.

- Bird ingestion
- Foreign object damage (FOD)
- Ice ingestion
- Sand and dust ingestion
- Atmospheric liquid water ingestion
- Corrosive atmosphere
- Humidity
- Icing
- Rain and hail ingestion
- Rotor vibration

Detailed requirements are given in US DoD JSSG-2007, FAR 33, MIL-STD-810F.

The outline of active control technologies described in this chapter results in detailed requirements for sensors and actuators. The following Table 2.3 gives an overview on required technologies, more details can be found in the references to each subchapter. Existing sensor and actuator technology will not be mentioned here.

Table 2.3: Sensor and Actuator Requirements for Active Control Technologies

Sensor and Actuator Requirements for Active Control Technologies					
	Technology	**Sensed Variable**	**Sensor Requirements**	**Controlled Variable**	**Actuator Requirements**
Inlet	Active Inlet Control	Static pressure	0 – 500Hz bandwidth +0.1% accuracy case-mounted installation	Inlet geometry, vortex generator geometry, flaps, jet, suction	Flow control bandwidth 0 – 2kHz 0 – 2% core mass flow Geometry control bandwidth 0-100Hz Supersonic inlet control 1 – 3Hz
	Active Noise Control	Dynamic pressure	100 kPa differential, 10 kHz, +0.5% FSO	Honeycomb geometry, acoustic waves	Piezoelectric Actuator, 2.5 – 5 mm deflection
Compressor	Active Surge Control	Static pressure	35 kPa dynamic range +0.2% accuracy 5 – 100 kHz bandwidth case-mounted installation	Jet, guide vane movement, bleed air	Strong dependence on stall/surge dynamics Bandwidth 80 – 150Hz full amplitude 500 – 600Hz small signal 1 – 4% core mass flow
	Active Flow Control	Static pressure	35 kPa dynamic range ±0.5% resolution 20 Hz – 100 kHz bandwidth for sensors (depending of the flow phenomena measured)	Jet (pulsed, zero-net-mass-flow) , suction, blowing, airfoil geometry change	Fluidic actuation devices installed in airfoil at different frequency ranges: a) 200 – 300Hz b) 500Hz – 5kHz c) 50 – 100kHz Steady blowing of < 2% core flow at 1 – 2Hz Shape memory alloys installed in airfoil for shape variation deployable within few seconds
	Active Clearance Control	Clearance	2.5 mm range, accuracy 25 µm 50 kHz bandwidth case-mounted installation	Casing geometry	Thermal, mechanical, pneumatic devices Actuation rate > 0.1mm/s bandwidth 1 – 5 Hz Force 10kN Stroke 3mm Resolution 0.02 mm

Sensor and Actuator Requirements for Active Control Technologies					
	Technology	**Sensed Variable**	**Sensor Requirements**	**Controlled Variable**	**Actuator Requirements**
	Active Vibration Control	Arrival time	Capacitance, eddy current or microwave probes accuracy < 25 µm 50 kHz bandwidth case-mounted installation	Airfoil geometry	Pressure > 3000 N/cm² deformation > 0.5mm installation in airfoil 1 – 30kHz bandwidth
Combustor	Combustion Instability Control	Static pressure	10 kPa dynamic range ±5% accuracy 1 kHz bandwidth	Fuel modulation, acoustic energy, jets, moving surface	High-band width actuation, typically 500Hz to 1kHz frequency range. Fuel flow modulation goal at 1 – 5% of mean flow
	Emission Control	Emissions (CO, CO_2, NOx)	±5% accuracy < 5 Hz bandwidth Installation in HPT	Fuel flow actuation	Schedule on emission sensing 5 – 10% of total fuel flow modulated at 0.1 – 1 Hz
	Burner Pattern Factor Control	Temperature	± 5°C accuracy < 1 Hz bandwidth Installation on HPT stator vanes	Fuel flow actuation	Fuel flow modulation on each nozzle 5 – 10% of total fuel flow modulated at 0.1 – 1 Hz
Turbine	Active Clearance Control	Clearance	2.5 mm range, accuracy 25 µm 50 kHz bandwidth case-mounted installation	Casing geometry	Thermal, mechanical, pneumatic devices Actuation rate > 0.1mm/s bandwidth 1 – 5 Hz Force 10kN Stroke 3mm Resolution 0.02 mm
	Cooling Air Control	Surface temperature turbine stator blade	Min resolution + 5° Steady state, 1 Hz	Total flow modulation or Individual blade flow modulation	1Hz bandwidth 20% modulation of baseline cooling flow
	Flow Control	Static pressure	Equivalent to compressor flow control Steady flow control may be based on operating point	Jets, boundary layer suction, plasma actuator	Plasma actuator bandwidth 10 – 200 Hz at 5kHz, voltage 5 – 25kV Steady blowing <0.1% of core flow

Sensor and Actuator Requirements for Active Control Technologies					
	Technology	**Sensed Variable**	**Sensor Requirements**	**Controlled Variable**	**Actuator Requirements**
Nozzle	Active Noise Control	No Sensor	N/A	Variable nozzle geometry, jets	Shape memory alloys 30mm actuation, stiffness <1mm deflection pulsed jets ~1 – 4 kHz, 0.6*Exhaust Velocity, 1% Engine flow
	Thrust Vectoring	Jet direction	Reaction force, optical position detection?	Nozzle geometry, jets	1.5% of core flow / 1.5 deg of vector angle
	Afterburner Stability Control	Dynamic pressure	40 – 800 kPa static, +-35kPa dynamic range, 20Hz – 10kHz, 220 – 650K	Nozzle geometry / area Fuel flow actuation	Existing afterburner actuators reaction time < 0.1s

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