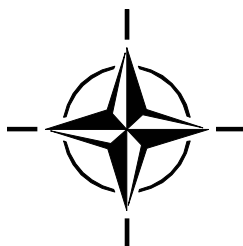AC/323(AVT-128)TP/255

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RTO TECHNICAL REPORT　　　　　　　　　**TR-AVT-128**

More Intelligent Gas Turbine Engines

(Des turbomoteurs plus intelligents)

This Report documents the findings of RTO Applied

Vehicle Technology (AVT) Panel Task Group 128.

Published April 2009

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This Report documents the findings of RTO Applied
Vehicle Technology (AVT) Panel Task Group 128.

by

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RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT   Applied Vehicle Technology Panel
- HFM   Human Factors and Medicine Panel
- IST   Information Systems Technology Panel
- NMSG   NATO Modelling and Simulation Group
- SAS   System Analysis and Studies Panel
- SCI   Systems Concepts and Integration Panel
- SET   Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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More Intelligent Gas Turbine Engines

(RTO-TR-AVT-128)

Executive Summary

Increased emphasis on aircraft safety, enhanced performance and affordability, and the need to reduce the environmental impact of aircrafts are being addressed through the concept of Intelligent Propulsion Systems. The key enabling technologies for these systems are the increased efficiencies of components through active control, advanced diagnostics and prognostics integrated with intelligent engine control, and distributed control with smart sensors and actuators. The emphasis throughout the report is on identifying the sensor and actuator needs, the current sensor and actuator technologies, and roadmaps for emerging technologies from the overall engine gas-path performance perspective.

Actively Controlled Components will mitigate challenges related inlet flow distortion and separation and noise; compressor aerodynamic losses and surge and stall; combustion instabilities, uneven temperature distribution, and pollution emission; turbine aerodynamic losses and leakages, high cycle fatigue, and limited airfoil durability; and jet noise, emission, and signature. The effectiveness of active control has been demonstrated in lab-scale tests, however significant efforts in R&D remain to implement these technologies. In particular, sensors and actuators for the high temperature environment in an aero engine are needed.

Intelligent Control and Health Monitoring with advanced model-based control architecture overcomes the limitations of state-of-the-art engine control and provides the potential of virtual sensors. "Tracking filters" are used to adapt the control parameters to actual conditions and to individual engines. Currently, health monitoring units are stand-alone monitoring units. Integration of both control and monitoring functions is possible, but certification issues have to be clarified. Adaptive models open up the possibility of adapting the control logic to maintain desired performance in the presence of engine degradation. Improved and new sensors are required to allow:

1) Sensing at stations with high operating temperatures; and

2) Additional monitoring of vibration, mass flows, fuel properties, exhaust gas composition, and gas-path debris.

Distributed Engine Control using high temperature electronics and open systems communications will reverse the growing trend of increasing ratio of control system weight to engine weight and also will be a major factor in decreasing overall cost of ownership. Challenges for implementation include need for high temperature electronics (located on or close to the sensing element), development of simple, robust communications (simplifying and reducing the wiring harness), and power supply for the on-board distributed electronics. With the limitation of standard silicon technology for current smart sensors, newer material technologies are required.

Sensors mainly require higher operational temperatures. Some progress can be made by changing the packaging and/or design of the current sensors, but sensor for locations close to the engine combustion chamber or afterburner do not exist. There is also a need for smart sensors, which would enable future distributed control architecture. A number of new sensors are being explored (gas composition, burning pattern factor, fuel property), and for other sensors rapid advances have been made (tip clearance). To meet the future sensor requirements, new fabrication and material technologies and advanced sensing principles are being explored.

Actuator requirements are addressed for three common actuation functions, namely:

1) Micro flow manipulation;

2) Large-scale flow switching; and

3) Mechanical manipulation.

Generic requirements are summarized in terms of operational environment and performance/capabilities depending on component applications. Developments towards these requirements must be intimately coupled to the specific application requirements in order to satisfy the overall constraints, including full system requirements, cost, maintenance, failure modes, etc. Established actuators and emerging technologies are being considered.

The report concludes with a roadmap for implementation of the various components and recommendations for sensor and actuator development priorities.

Des turbomoteurs plus intelligents
(RTO-TR-AVT-128)

Synthèse

Une attention plus grande portée à la sécurité des aéronefs, à l'amélioration des performances à moindre coût, ainsi que le besoin de réduire l'impact environnemental des aéronefs sont pris en compte actuellement via le concept des Systèmes de Propulsion Intelligents. Les capacités technologiques clés proviennent de l'efficacité grandissante des composants grâce au contrôle automatique généralisé, aux diagnostics et aux pronostics évolués intégrés dans des commandes moteurs intelligentes ainsi que du contrôle distribué avec des capteurs et des servomoteurs intelligents. Ce rapport met l'accent sur l'identification des besoins en capteurs et en servomoteurs, des technologies actuelles sur les capteurs et les servomoteurs et des feuilles de route pour les technologies émergeantes du point de vue des performances des turbines à gaz.

Le recours à des **Composants Attentivement Pilotés** permettra de remédier aux problématiques liées à la distorsion et à la séparation et au bruit du flux d'entrée d'air ; aux pertes et aux fuites aérodynamiques et au décrochage du compresseur ; aux instabilités de combustion, à la répartition irrégulière de la température et aux émissions polluantes ; aux pertes et aux fuites aérodynamiques des turbines, aux grands cycles de fatigue et à la durabilité limitée du profil aérodynamique ; et au bruit, à l'émission et à la signature des turboréacteurs. L'efficacité du contrôle automatique généralisé a été démontrée au cours d'essais en laboratoire, cependant, des efforts significatifs en R&D sont à faire afin de mettre en application ces technologies. En particulier, des capteurs et des servomoteurs capables de fonctionner dans un environnement à température élevée dans un moteur d'avion sont nécessaires.

La Surveillance et le Contrôle Automatiques dans le cadre d'une architecture de contrôle modélisée et évoluée permet de surmonter les limitations du contrôle actuel des moteurs et fournit le potentiel de capteurs virtuels. « Des filtres de poursuite » sont utilisés pour adapter les paramètres de contrôle aux conditions réelles et aux moteurs séparés. Actuellement, les dispositifs de surveillance de bon fonctionnement sont autonomes. L'intégration à la fois du contrôle et de la surveillance est possible, mais les questions d'homologation doivent être clarifiées. Des modèles souples rendent accessibles la possibilité d'adapter la logique du contrôle pour maintenir les performances désirées en présence d'une dégradation du moteur. Des capteurs nouveaux et améliorés sont nécessaires pour permettre :

1) Le sensing dans des emplacements à températures de fonctionnement élevées ; et

2) Le suivi complémentaire des vibrations, des débits de masse, des propriétés du carburant, de la composition des gaz d'échappement et des débris sur la trajectoire des gaz.

Le Contrôle Moteur Distribué utilisant de l'électronique à température élevée et des systèmes de communications ouverts inversera la tendance croissante actuelle vers une augmentation de la proportion de la masse dédiée au système de contrôle par rapport à la masse du moteur et sera aussi un facteur majeur en vue de la réduction du coût total de possession. Les défis de sa mise en œuvre comprennent le besoin en électronique fonctionnant à température élevée (situé sur ou près de l'élément du sensing), le développement de communications simples et robustes (simplification et réduction du faisceau électrique) et l'alimentation électrique pour la distribution de l'électronique de bord. A cause de la limitation de la technologie standard à base de silicone pour les capteurs intelligents actuels, des technologies à base de matériaux plus récents sont nécessaires.

Les capteurs requièrent principalement des températures de fonctionnement plus élevées. Des progrès peuvent être réalisés en changeant le conditionnement et/ou la conception des capteurs actuels, mais les capteurs destinés à être situés près de la chambre de combustion ou de la postcombustion n'existent pas. Il existe aussi un besoin en capteurs intelligents destinés à bâtir l'architecture de contrôle distribué à venir. Un certain nombre de nouveaux capteurs sont à l'étude (composition des gaz, taux de combustion, propriétés du carburant) et pour d'autres capteurs, des progrès rapides ont été réalisés (mesure du jeu en tête d'aube). Pour satisfaire aux exigences sur les futurs capteurs, de nouvelles techniques de fabrication et de nouveaux matériaux ainsi que des principes évolués de « sensing » sont à l'étude.

Pour les exigences concernant les **servomoteurs**, trois fonctions génériques sont abordées, à savoir :

1) La manipulation des micro-flux ;

2) La commutation en large flux ; et

3) La manipulation mécanique.

Les exigences génériques sont résumées en termes d'environnements opérationnels et performances/ capacités en fonction des applications des composants. Les développements liés à ces exigences doivent être intimement couplés aux exigences sur les applications spécifiques afin de satisfaire à l'ensemble des contraintes y compris celles relatives au système dans son ensemble, au coût, à la maintenance, aux pannes etc. Les servomoteurs courants et les technologies émergeantes sont pris en considération.

Le rapport conclut par une feuille de route sur la mise en œuvre des divers composants et les recommandations sur les priorités de développement des capteurs et des servomoteurs.

Chapter 1 – INTRODUCTION

by

**Sanjay Garg (NASA Glenn Research Center) and
Hany Moustapha (Pratt and Whitney Canada)**

With the increased emphasis on aircraft safety, enhanced performance and affordability, and the need to reduce the environmental impact of aircrafts, there are many new challenges being faced by the designers of aircraft propulsion systems. There is significant investment being made by various NATO countries in development of advanced controls and health management technologies that will help meet these challenges through the concept of Intelligent Propulsion Systems. The key enabling technologies for an Intelligent Propulsion System (see Figure 1.1) are the increased efficiencies of components through active control, advanced diagnostics and prognostics integrated with intelligent engine control to enhance operational reliability and component life, and distributed control with smart sensors and actuators in an adaptive fault tolerant architecture. Development of appropriate sensors and actuation systems is critical to affordable and reliable implementation of the technologies for a more intelligent gas turbine engine.

Multifold increase in propulsion system Affordability, Capability
Environmental Compatibility, Performance, Reliability and Safety

Active Control Technologies
for enhanced performance
and reliability, and reduced
emissions
- active control of
combustor, compressor,
vibration etc.
- MEMS based control
applications

Advanced Health
Management technologies
for self diagnostic and
prognostic propulsion
system
- Life usage monitoring and
prediction
- Data fusion from multiple
sensors and model based
information

Distributed, Fault-Tolerant Engine Control for
enhanced reliability, reduced weight and optimal
performance with system deterioration
- Smart sensors and actuators
- Robust, adaptive control

**Figure 1.1: Advanced Control and Health Management Technologies
for "More Intelligent Engines" [1.1], [1.2], [1.3].**

The objective of this report is twofold:

1) Help the "Customers" (NATO defence acquisition and aerospace research agencies) understand the state-of-the-art of intelligent engine technologies, how these technologies can help them meet challenging performance and operational reliability requirements for aircraft engines, and what investments need to be made in sensor and actuator technologies to enable the various capabilities of "Intelligent Engines" so that limited resources are used in a most efficient manner; and

2) Help the "Researchers" and "Technology Developers" for sensors and actuators identify what sensor and actuator technologies need to be developed to enable the "Intelligent Engine" concepts so that their research efforts can be focused on closing the gap from current capability to that needed to meet identified requirements, and also increase their awareness of "requirements" that need to be met other than performance (such as cost, durability, etc.) to enable the transition of technology to a product. This latter emphasis helps ensure that the "non-performance" requirements are taken into consideration in developing solutions to meet performance requirements, and the limited resources are not "wasted" on technology paths which are not amenable to transition into a product.

The overall technology areas that fall under the umbrella of "intelligent engines" are too broad to be covered by this report. For example, just the component optimization will cover many areas as identified in Figure 1.2. Similarly, the area of diagnostics and prognostics will cover all the components shown in Figure 1.2 with a significant technology investment in vibration monitoring, diagnostics for accessories, etc., and including technologies for ground maintenance.
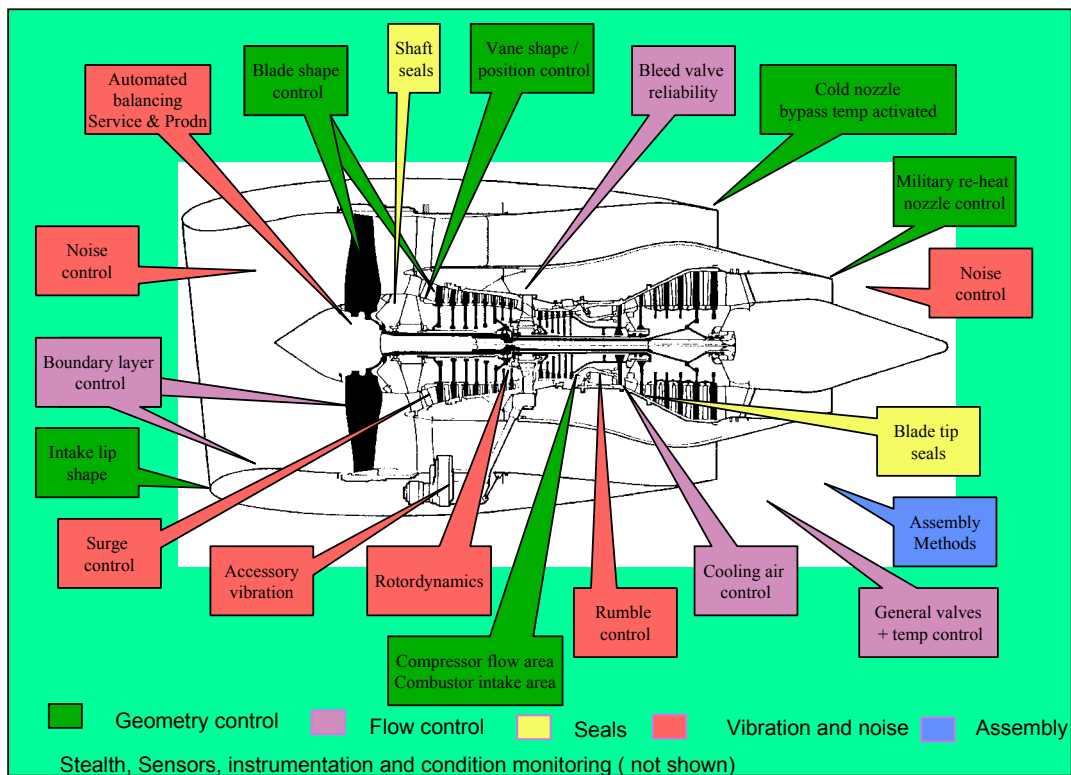
Figure 1.2: Identified Opportunities for Adaptive Optimization within a Gas Turbine Engine [1.4].

To keep the current effort manageable, the focus of this report is on "On-Board Intelligence" to enable safe and efficient operation of the engine over the life time, and adapt to changing internal and external environment to provide "optimum" achievable performance based on operation mode and current condition. The discussions in this report are limited to:

1) Technologies for active control of components in the gas path to enhance performance and reduce emission and noise;

2) Intelligent control and condition monitoring from the overall engine gas path performance perspective; and

3) Advanced control architecture concepts such as distributed engine control.

The emphasis throughout the report is on identifying the sensor and actuator needs to realize these intelligent engine concepts with the ultimate objective being to identify sensor and actuator technology development roadmaps. The organization of the report is briefly described in the following.

Chapter 2 discusses various concepts for active control of engine gas path components such as inlet, compressor, combustor, turbine and nozzle. Such components have been designed for optimum component performance within some overall system constraints and the control design problem has been to transition the operating point of the engine from one set point to another in a most expedient manner without compromising safety. With the advancements in information technologies, the component designers are beginning to realize the potential of including active control into their component designs to help them meet more stringent design requirements and more affordable and environment friendly propulsion systems. The following topics are discussed with respect to each gas path component:

1) Advantages and limitations of passive component design and benefits of active control to further increase operational flexibility and efficiency of each component;

2) Performance objectives for active component control and various high level approaches – what will be controlled and how. For some of the most promising approaches, the state of the art is discussed along with technical gaps and challenges; and

3) Performance and operating environment specifications for sensors and actuators to enable the active component control capability.

Chapter 3 describes the various aspects of intelligent engine control and condition monitoring from an overall gas path system perspective. The need to have more reliable and safe engine service, to quickly identify the cause of current or future performance problems and take corrective action, and to reduce the operating cost requires development of advanced diagnostic and prognostic algorithms. The objective for this health / condition monitoring technology is to maximize the "on wing" life of the engine and to move from a schedule based maintenance system to a condition based system. The chapter provides a brief description of state-of-art of engine control (system level) and inherent limitations in current architecture. Subsequently objectives for intelligent engine control are described including simplifying control design (such as direct or model based nonlinear approaches), adapting performance to engine degradation, extending on-wing life, and improving FDIA (Fault Detection, Isolation and Accommodation), prognostics and accommodation via corrective action. An overview of approaches to achieve these objectives is provided. For the various approaches, the technology development needs for modeling, control algorithm and hardware, and new sensors are described, with an emphasis on the latter. To keep the scope manageable, the discussion of diagnostics and prognostics technologies is limited to that required for achieving "closed-loop" control objectives. The focus of advanced control schemes is on developing algorithms that are implemented in the FADEC (Full Authority Digital Engine Control) in the form of software without any hardware changes on the engine in terms of any additional control effectors/actuators. The chapter is organized into five sections:

1) State-of-the-art of engine control;

2) Model based control;

3) On-board condition/health monitoring;

4) Adaptive control; and

5) Challenges and sensor needs to enable more intelligent control and health monitoring.

Chapter 4 discusses the technologies required to move from the current highly centralized engine control architecture to a more distributed control architecture to reduce the weight ratio of control system to engine and simplify the complexity of a centralized FADEC. The state of the art engine control architecture using a central FADEC is briefly described along with its limitations and the need for distributed control. Various options for distributed control architecture and the pros and cons of these options are discussed. Challenges due to the harsh environment of the engine, as summarized in Figure 1.3, and weight and volume limitations imply the need for developing high temperature electronics and data communication hardware to enable smart, self diagnostic sensors and actuators to fully utilize the benefits of distributed control architecture.
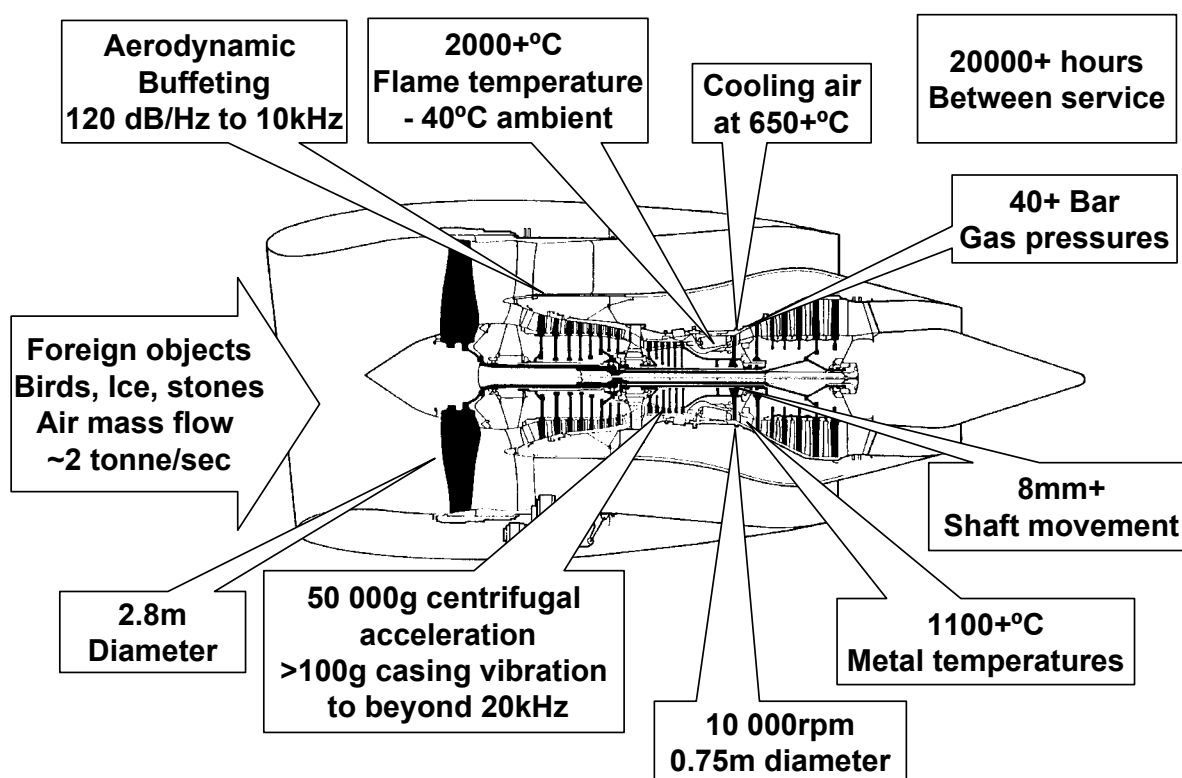
Figure 1.3: Environment within an Aircraft Gas Turbine Engine [1.4].

Chapter 5 summarizes the requirements, other than performance, that a sensor or actuator technology needs to meet in order to be considered for implementation on an engine. Such requirements relate to Technology Readiness Level (TRL) [1.5], durability, reliability, volume, weight, cost, etc. The objective is to help educate the researchers or technology developers on the extensive process that the technology has to go through beyond just meeting "performance" requirements before it can be implemented on a product. The discussion includes:

1) A summary of the value analysis that is done to make a "business case" to consider a new technology (sensor, actuator, etc.) for implementation on a production engine (new design or a variant); and

2) The evaluation steps that a prototype goes through for the technology to be considered to be mature enough for the engine company or customer to pay the development costs needed to insert the technology into product.

Chapter 6 focuses on sensor requirements with the objective to identify the status of current and future potential sensing technologies and a roadmap for sensor developments. The discussions are based on generic sensor requirements, which have been derived from performance requirements of Chapters 2 to 4. Generic requirements for all sensing variables are defined by measurement capability (range, bandwidth, resolution, and accuracy) and the capability to withstand certain operation environments (temperature and vibrations). Current sensing principles and sensor technologies which can meet these requirements are described. New sensing principles and their application to future potential sensors are summarized. The need for high-temperature operation capability and smart sensors is emphasized. RandD needs / gaps and roadmaps for these future sensor technologies are discussed. A preliminary assessment of various sensing approaches against the "non-performance" requirements discussed in Chapter 5 is also provided. The chapter concludes with a table which summarizes the following for each of the sensed variables: environmental and performance requirements; applications; potential technologies; current TRL and years to achieve TRL 6 (prototype demonstration in a relevant environment); and expected challenges.

Chapter 7 identifies generic actuators requirements based on the component specific actuator requirements of Chapter 2. For the main application areas, three generic actuation principles are defined and addressed. The issues and considerations which must be made in the choice of any actuator for a specific application are reviewed followed by an assessment of available actuators and their application to specific components. For future development needs a selection of the more promising emerging technologies are summarized, and the potential application to specific components is discussed. The chapter concludes with a table which summarizes the following for each of the actuator variables: the environmental and performance requirements; applications; potential technologies; current TRL and years to achieve TRL 6; and expected challenges.

Chapter 8 provides a summary of the chapters and summarizes in a table for the main "intelligent gas turbine" technology/component areas both the years to achieve TRL 6 and the potential benefits. The chapter concludes by providing some recommendations on priorities for sensor and actuator technologies development based on the potential for meeting the mid to long term needs of more intelligent engine capabilities.

The report is based on activities of the RTO Task Group AVT-128 "More Intelligent Gas Turbine Engines". Details regarding participants, Technical Activity Proposal (TAP) and Terms of Reference (TOR), and dates and places of meeting are described in [1.6] to [1.9]. AVT-128 is a follow-on activity of RTO Task Group AVT-078 "MEMS Applications to Air, Land, and Sea Vehicles". Applications of interest to the present report included active flow control and active control of gas turbine components [1.10]. A roadmap for potential gas turbine applications was developed [1.11].

1.1 REFERENCES

[1.1]   Annex B1.2 – Sanjay Garg, *"Controls and Health Management Technologies for Intelligent Aerospace Propulsion Systems"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE.

[1.2]   Annex C.2 – S. Garg, *"Controls and Health Monitoring Technologies for Intelligent Propulsion Systems"*, NASA TM-2004-212915.

[1.3]   Annex C.4 – S. Garg, *"NASA Glenn Research in Controls and Diagnostics for Intelligent Propulsion Systems"*, NASA TM-2005-214036.

[1.4]   J. Webster, *"Are Shape Memory Alloys about to come to age for gas turbine applications?"*, ISABE Conference, Beijing, September 2007, Paper Number 1294.

[1.5]   Appendix 1 – RTB Endorsed Proposed NATO Hardware TRL Definitions (24 September 2007).

[1.6]   Appendix 2 – AVT-128 Task Group Participants.

[1.7]   Appendix 3 – Technical Activity Proposal (TAP) for AVT-128.

[1.8]   Appendix 4 – Terms of Reference (TOR) for AVT-128.

[1.9]   Appendix 5 – Task Group Meetings (Dates and Places).

[1.10] Annex C.6 – TR-AVT-078-Chapter 4 MEMS Applications.

[1.11] Appendix 6 – Roadmap for MEMS Application to GTE Active Control (TR-AVT-078).

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.
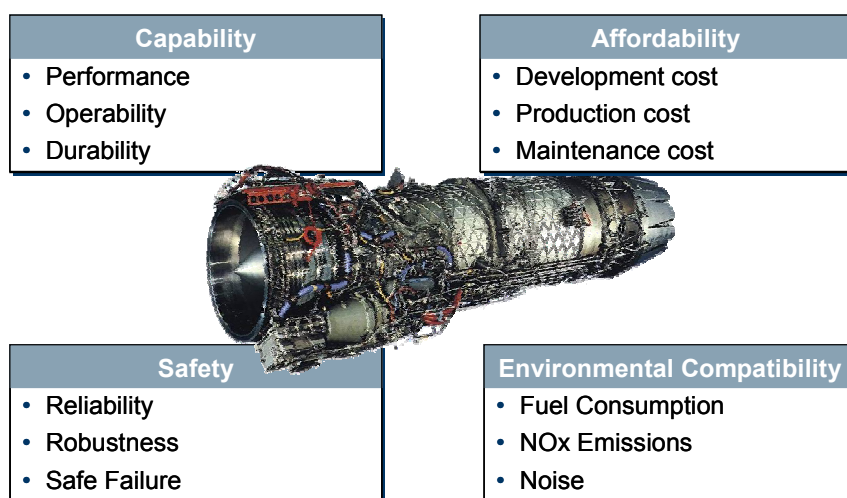
Figure 2.1: Requirements of a Modern Aircraft Engine.

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.
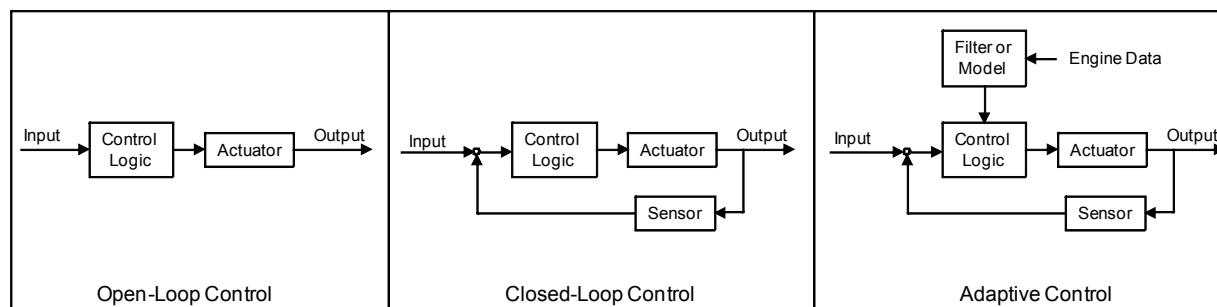
Figure 2.2: Different Control Approaches.

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.

High Mass Flow Engine
Cross-Wind condition

Low Mass Flow Engine
Wind-Milling conditions
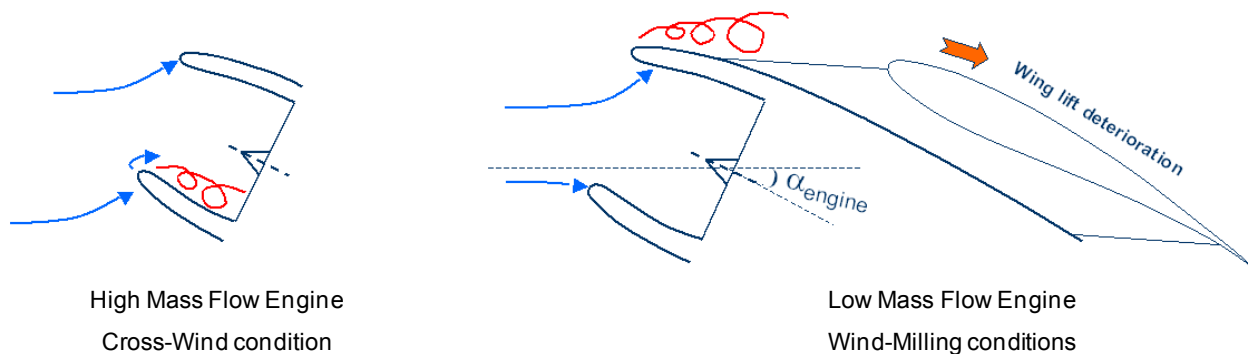
Figure 2.3: Flight Conditions Leading to Flow Separation in the Engine Inlet.

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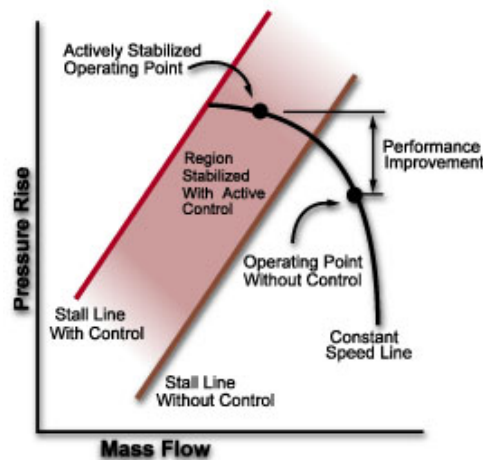
Figure 2.4: Enhanced Compressor Operating Point by Active Surge Control [2.23].

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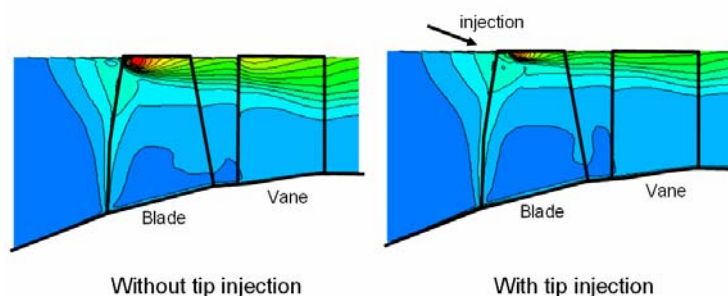
Figure 2.5: Entropy Contours Close to the Surge Point during Active Surge Control by Tip Injection.

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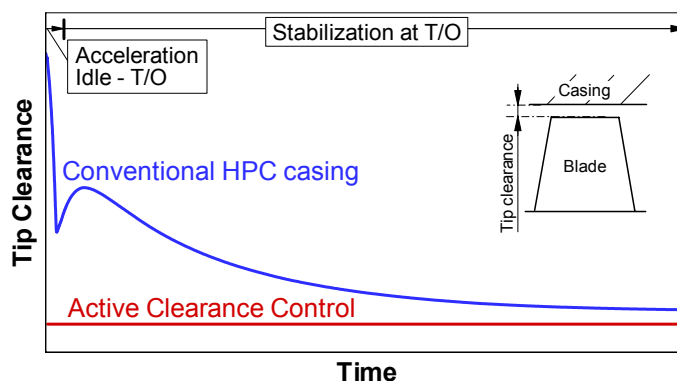
**Figure 2.6: HPC Tip Clearance for an Acceleration
Followed by a Stabilisation at High Power Setting.**

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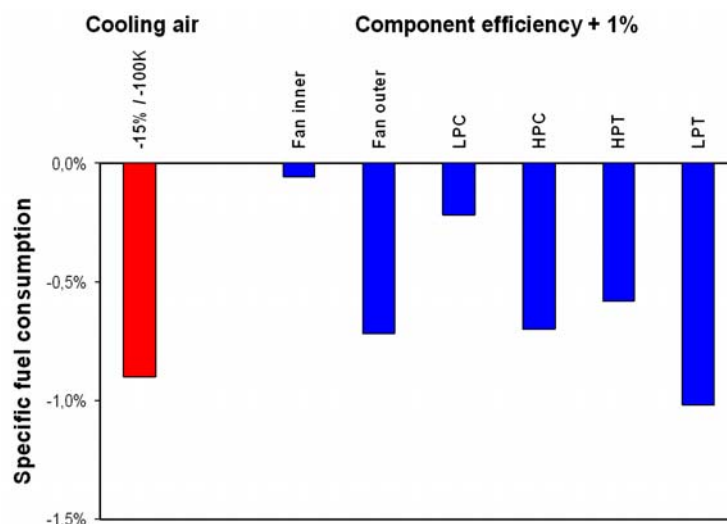
**Figure 2.7: Typical Exchange Rates on Fuel Consumption
in a Two-Spool Turbofan Engine [2.104].**

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.
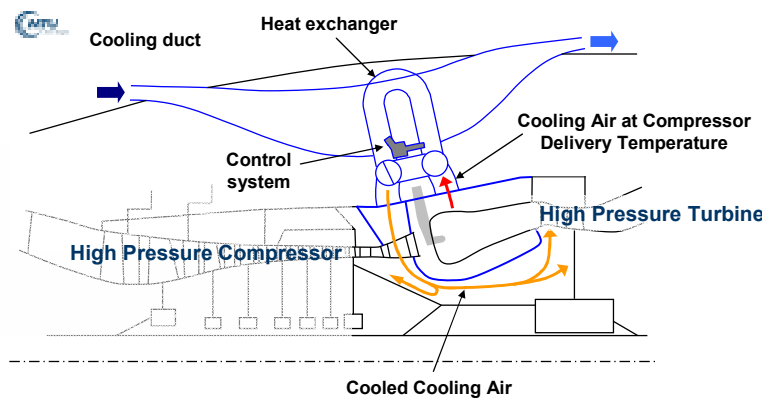
Figure 2.8: Gas Turbine Configuration with Cooling Air Cooling.

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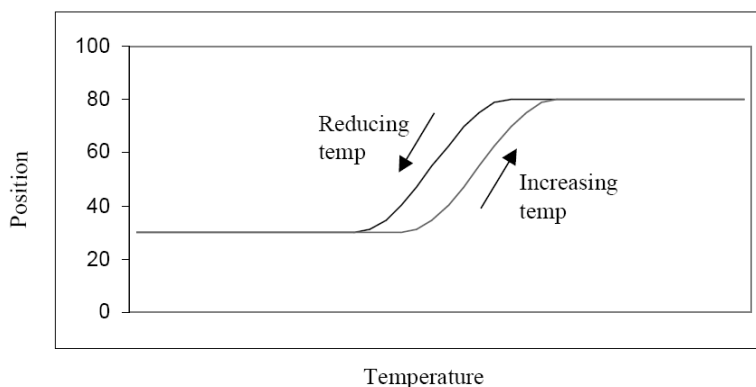
Figure 2.10: Position/Shape Control by SMAs [2.126].

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

span	**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\n\nGeometry 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\n\nBandwidth 80 – 150Hz full amplitude 500 – 600Hz small signal\n\n1 – 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:\n\na) 200 – 300Hz\n\nb) 500Hz – 5kHz\n\nc) 50 – 100kHz\n\nSteady blowing of < 2% core flow at 1 – 2Hz\n\nShape 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**
Combustor	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
	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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Chapter 3 – INTELLIGENT CONTROL AND HEALTH MONITORING

by

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ABSTRACT

Advanced model-based control architecture overcomes the limitations state-of-the-art engine control and provides the potential of virtual sensors, for example for thrust and stall margin. "Tracking filters" are used to adapt the control parameters to actual conditions and to individual engines. For health monitoring stand-alone monitoring units will be used for on-board analysis to determine the general engine health and detect and isolate sudden faults. Adaptive models open up the possibility of adapting the control logic to maintain desired performance in the presence of engine degradation or to accommodate any faults. Improved and new sensors are required to allow sensing at stations within the engine gas path that are currently not instrumented due in part to the harsh conditions including high operating temperatures and to allow additional monitoring of vibration, mass flows and energy properties, exhaust gas composition, and gas path debris. The environmental and performance requirements for these sensors are summarized.

3.1 INTRODUCTION

Ref. [3.1] provides an overall summary of the state-of-the-art of engine control and health monitoring which is reproduced here to provide the reader with background information. Typical aircraft engine control systems maintain fan speed or engine pressure ratio to regulate thrust which is not directly measurable. The control logic is generally based on a variant of a Proportional-Integral scheme combined with limit logic as shown in Figure 3.1. This limit logic consists of a series of *min select* and *max select* blocks, each of which selects a fuel flow rate command based on various physical limits, acceleration/deceleration schedules (maximum rotor speed rate-of-change as a function of rotor speed), and the current operating state (speed governor loops).
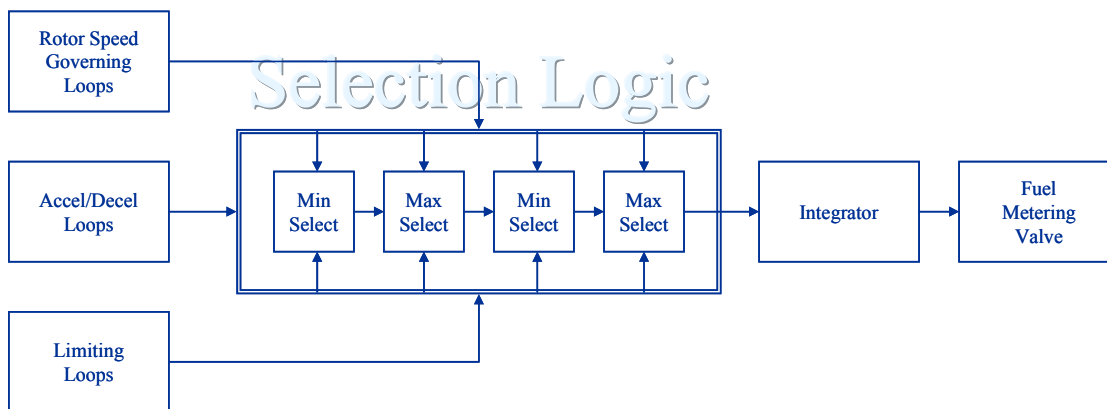
Figure 3.1: Block Diagram of Typical Engine Control Law Architecture.

The various on-wing health monitoring systems of today, which are a collection of separate, unrelated technologies, provide a basic level of monitoring. Their capabilities are relatively limited and the information they provide is used mostly to initiate maintenance actions, not for real-time decision-making. One instance where the information is used on wing is for sensor validation. The controller has some simple logic to perform basic limit or rate of change checks on engine sensors and actuators. In some cases, on-board engine models are used in conjunction with the controller's own sensor voting scheme to help determine which sensor is correct when redundant sensors disagree. The controller has the additional responsibility of checking whether a speed red-line has been exceeded, and reducing fuel flow when it has. Current engine vibration monitoring systems sample at a relatively low frequency – too low to capture much significant or useful information on the vibratory modes of the system. They check the vibration magnitude to determine that it is within a normal range. Magnitudes that are too high might indicate a bearing failure or engine imbalance, magnitudes that are too low might indicate a faulty sensor or seized engine. Lubrication system monitoring is performed using a magnetic chip detector to determine the existence of ferrous debris in oil. This is an indication of part wear. Life cycle counts are performed on-wing. Engine parts, especially those in the hot section, may experience a maximum number of severe thermal transients before they must be retired. Each time the engine goes through a start-up transient, the life cycle count for each of the critical components is incremented. This way, part life is tracked as a function of use to facilitate scheduled maintenance.

While these traditional control and diagnostic techniques are time-tested and reliable, advanced techniques provide the promise to meet the challenging requirements of improved fuel efficiency, increased durability and life, decreased life cycle costs, and improved operations. Using an on-board engine model to meet the challenging control and diagnostics requirements has emerged as the most viable approach. The continuing increase in computer processing capability has reached the point where the use of model based algorithms for diagnostics and control of aircraft engines has become practical. Previously the complexity of the thermodynamic cycle model has made their use impractical. Model based technologies offer the potential for creating intelligent propulsion systems – defined as self-diagnostic, self-prognostic, self-optimizing, mission adaptable and inherently robust – that far exceed current systems in performance, reliability and safety [3.1].

The concept of model-based control and diagnostics is shown in Figure 3.2. The engine model is driven with the measured engine inputs (shown here as control signals, u, but usually also includes environmental conditions) to obtain the predicted engine outputs $\hat{y}$. The predicted outputs are differenced with the measured engine sensor outputs, y, to form residuals, which can be used to diagnose engine health and adapt the model.
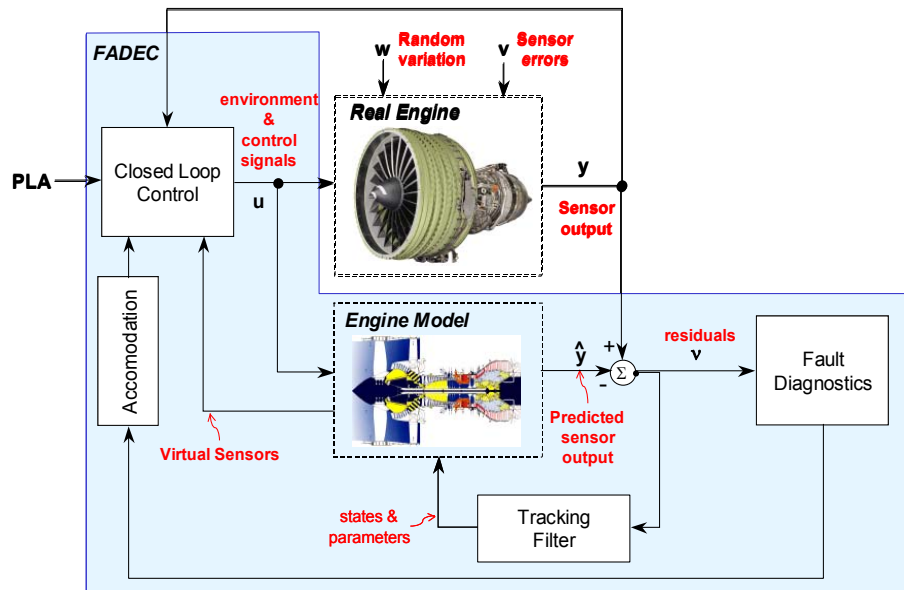
Figure 3.2: Model Based Control and Diagnostics Concept.

Historically the control architecture has relied on Single Input Single Output (SISO) feedback loops. Transition to model based control can occur in several ways. First, faults can be accommodated by changing the control laws, in a predetermined way, when a fault is detected. The changes are designed to, at a minimum, take the engine to a safe state, and preferably allow the engine to operate safely with best, although probably degraded, performance. Secondly, the model allows the loop to be closed on unmeasured values (e.g. thrust, stall margin) for which there is no sensor, i.e. virtual sensors. Finally, in its most advanced form, the model is used directly in the control enabling the control to automatically adjust as the model adapts to the mission, deterioration, faults, weather, etc. Here the control can be designed to maximize performance without excessive conservatism.

This chapter provides an overview of the progress and challenges in using model based approach to intelligent control and health monitoring of aircraft engines. The chapter is organized into three sections – model based control; on-board condition / health monitoring; and adaptive control. The chapter concludes with a summary of sensor needs to enable intelligent control and health monitoring. The focus of these technologies is on developing algorithms that are implemented in the FADEC (Full Authority Digital Engine Control) in the form of software without any hardware changes on the engine in terms of any additional control effectors/actuators.

3.2 MODEL-BASED CONTROL

The SISO control approach is simple and adequate for conventional engines where the main fuel is indeed the dominant actuator and the control requirements are not very stringent. However, it is inadequate for engines where there are multiple actuators with significant interaction between the actuators and the engine outputs to be controlled, e.g. a variable cycle engine or advanced commercial/military engines. A more advanced model-based Multi Input Multi Output (MIMO) control architecture shown in Figure 3.3 overcomes the limitations of the SISO architecture, where all available control actuators (e.g. main fuel, variable geometries, exhaust nozzle area, clearance control actuator) are manipulated in a coordinated manner to achieve multiple objectives like thrust and speed regulation, and limits on temperatures, pressures, stall margins, etc.
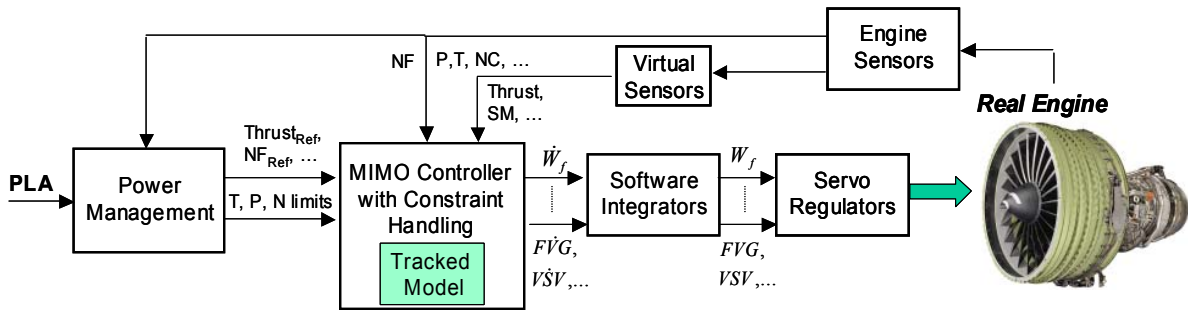
Figure 3.3: MIMO Control Architecture for Enhanced Control and Accommodation.

In such a model-based control structure, the model can provide outputs for which there is no sensor, i.e. virtual sensors. These virtual sensors provide the capability to directly control unmeasured variables such as thrust and stall margin. Additionally, the model outputs can be used for sensor fault accommodation, where model output (predicted sensor reading) temporally replaces a failed sensor, and virtual duplex redundancy, where the model output permanently replaces one sensor in a duplex pair. As confidence is gained with implementation of model-based control, it is envisioned that these virtual sensors can eventually eliminate the need for some of the sensors where the model output permanently replaces a simplex sensor or duplex pair.

One of the major challenges in implementation of model-based control is to have the model reflect the actual condition of the engine. Historically a single, fleet average model is used based on known or expected fleet average performance of a particular engine type. Use of this average model to predict individual engines within a fleet results in varying model errors, corresponding to how each engine deviates from the average. The resulting model error couples with normal flight variations in the input conditions to cause systematic error in the residuals, which limits the capability of the model to accurately predict the unmeasured variables. Also, when a fault occurs in the engine, if this fault is not appropriately reflected in the model, it can cause significant errors in estimation of the unmeasured variables. Thus, it is important to ensure that the model being used for control reflects the true condition of the engine. Typically a "tracking filter" is used to estimate model parameters related to deterioration causing the model to "track" the individual engine over time. Additionally the tracked parameters can be monitored to provide an indication of the health of the components of the engine, e.g. the level of deterioration (see On-board Condition Monitoring Section below). Typically abrupt faults are detected with the diagnostics algorithm and slowly changing health assessed by monitoring these tracked parameters.

Error reduction is accomplished by applying state and parameter estimation techniques to adapt model parameters to the individual engines. An appropriate set of model parameters must be identified which address the nature of the model mismatch and are also observable from the measured outputs. Because the engine model is nonlinear and the parameter estimation problem itself is nonlinear, an Extended Kalman Filter (EKF) formulation is typically chosen [3.2] [3.3]. Many variations of the EKF exist to meet varying performance and computational requirements. For example an iterated EKF (IEKF) is often used for remote services implementation on the ground and a linearized or suboptimal gain scheduled Kalman filter is used on-wing when computational constraints warrant. A general description of these techniques can be found in Gelb [3.4] or other texts on optimal estimation.

During transient operation of the engine, such as takeoff, an engine state estimator is employed along with the model parameter estimator so that the effects of engine states are accounted for and separated from the parameter

estimates. Engine states are typically the spool speeds and various metal temperatures. The resulting model parameter estimates for a particular engine at a particular time are used in that model to reduce the systematic errors in the residuals. For example Figure 3.4 shows the residuals over several Monte Carlo simulations (random deterioration) where the tracking filter is engaged midway through (25 sec).
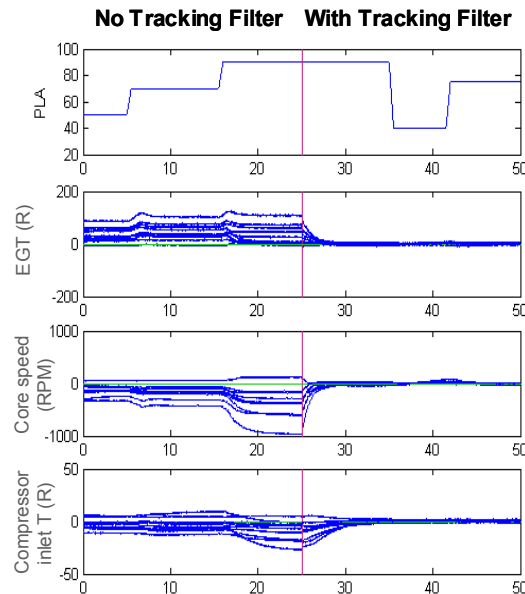
Figure 3.4: Monte Carlo Simulation of a Tracking Filter.

The parameter adaptation can be continuous or periodic but must be performed with sufficiently high bandwidth to keep the effects of normal deterioration out of the residuals, but low enough so that abnormally rapid shifts in performance are fully observed in the residuals.

The MIMO controller, with multiple available closed-loop control actuators, can be designed to meet the desired performance objectives (e.g. thrust) as well as optimize other important objectives like minimize specific fuel consumption (SFC) or minimize turbine temperature to enhance engine life, depending on the mission objectives. For instance, during take-off the controller can be designed to minimize turbine temperatures, while in cruise operation it can be designed to minimize SFC. The availability of model-based virtual sensors allows direct control to important un-sensed variables, e.g. thrust, stall margins, turbine temperatures. Also, the availability of a tracked engine model that is matched to a particular engine as it slowly deteriorates over time enables improved controls and performance optimization with reduced conservatism. Finally, the model-based MIMO control architecture also lends itself to automated fault accommodation, wherein the updated model reflects the specific component fault and forms the basis for an updated control action. Ref. [3.5] provides an excellent example application of model-based control to aircraft engines.

3.3   ON-BOARD CONDITION MONITORING

Engine Condition (or Health) Monitoring (ECM) systems comprise an on-board (or on-engine) and on-ground part. An example of the total on and off engine system as applied to the Trent 900/A380 program is depicted in the diagram in Figure 3.5, which shows the key data flow paths [3.6].
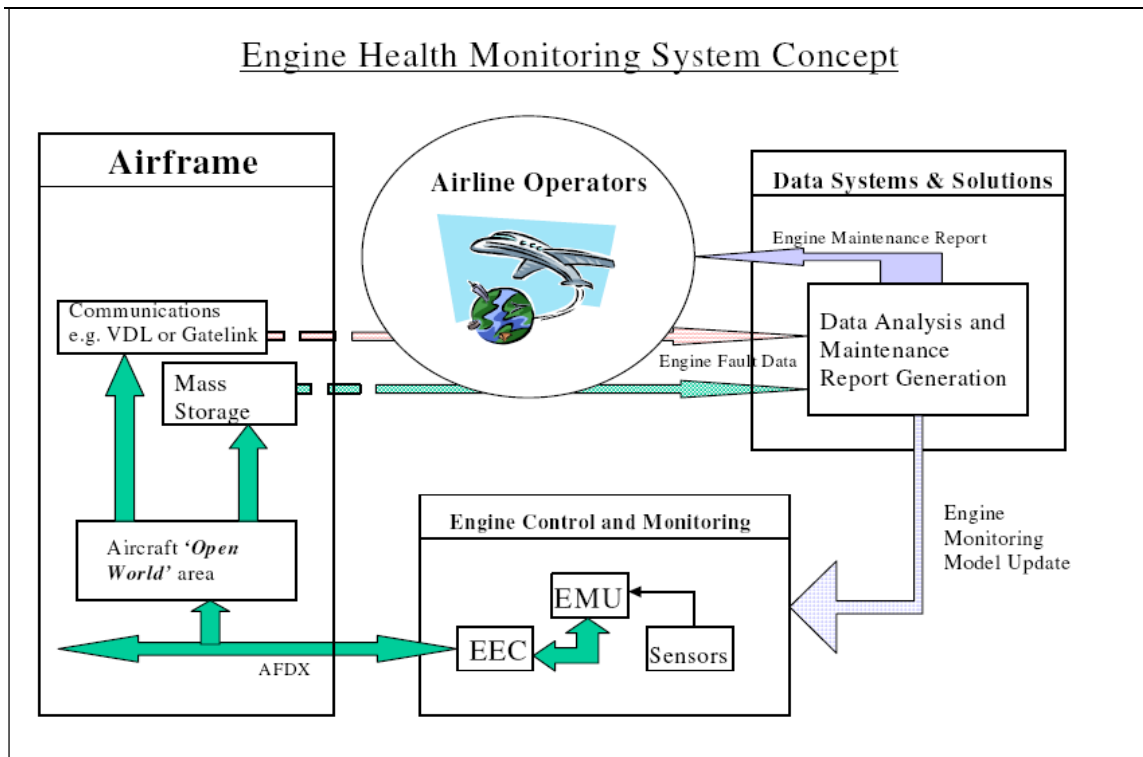
Figure 3.5: T900 Engine Condition Monitoring Concept.

The on-board part of the ECM system has been for a long time embedded in the Electronic Engine Control (EEC) unit of Full Authority Digital Engine Control (FADEC) system, or in some cases the Engine Monitoring Unit (EMU) was a standalone unit either engine or airframe mounted.

With increased performance and affordability of the on-board computer there is a recent trend, at least in large civil engines, to have a standalone, engine mounted EMU. Such an EMU has access to continuous data, powerful computing capability that provides on-board analysis, can process large volume of data which are impractical to transfer to the ground and can look also for transient effect and do this throughout the duration of the whole flight [3.6].

The reasons for having EMU separated from EEC and installed on engine are:

1) Different level of criticality, with FADEC having highest criticality level and requiring redundancy and software level A and EMU being mostly single channel with non-flight critical software level. Such a separation has positive impact on development cost of both EEC and EMU, MTBF (mean time between failure) of the control system is not compromised by "non-control" sensors, electronics and software of engine condition monitoring.

2) Different life cycle. Engine control unit shall be mature at engine certification; engine monitoring system has initial functionality and diagnostic algorithms evolve with experience from the engine operation.

3) Condition monitoring detection limits can adapt to an individual engine, account for the normal degradation and performance deviations, and therefore reduce false alarms. In keeping the EMU as an

integral part of the engine, the logistic problems that would arise when an engine is removed, replaced or otherwise separated from its health status 'memory' are avoided.

Example of ECM system structure for T900 is in Figure 3.6 [3.7]. The close proximity of the EMU and the associated monitoring sensors on the engine gives the capability to capture and process high bandwidth signals without the constraints of limited digital transmission rates, significant weight of cabling over long runs, and increased exposure to electrical radiation and lightning threats [3.6].
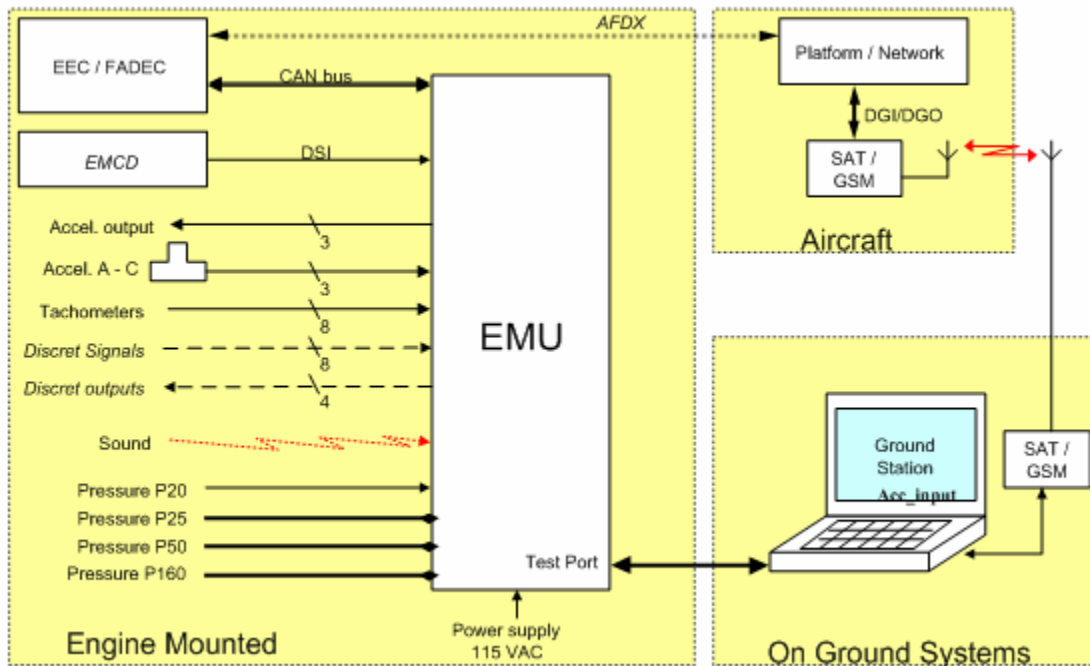
Figure 3.6: Structure of T900 Engine Condition Monitoring System.

The functions of the state of the art military prognostics and health management typically include fault detection and isolation, advanced diagnostic, predictive prognostics, useful life remaining and time to failure predictions, components life tracking, performance degradation trending, warranty/guarantee tracking, engine health reporting, aids in decision making, fault accommodation, information fusion and reasoners, information management to provide Right Information to Right People at Right Time.

The focus of this section is on on-board condition monitoring from the perspective of gas path performance diagnostics. Gas path performance diagnostics involves estimating the values of specific variables associated with the gas path components, or changes in these values that might indicate a fault. It is important to distinguish between the general health of the engine gas path components and sudden faults. The general health of the engine is equivalent to its level of degradation or effective age, and is the baseline from which changes are measured. In the gas path, the health condition of each component is defined by its efficiency and other parameters that change slowly. In general there are not enough engine sensors available to allow estimation of these *health parameters* in flight. Some diagnostic schemes relate faults to abrupt changes in the parameters associated with component health. Thus, on-line monitoring of unmeasurable variables is the basis for many fault detection and isolation approaches [3.8]. The information flow diagram in Figure 3.7 indicates

how damage and wear is related to degraded performance [3.9]. Many linear and nonlinear techniques have been applied to this problem, but without the addition of diagnostic sensors, the problem will remain. The estimation problem arises because the number of health parameters exceeds the number of measurements, which means that the problem is underdetermined and thus the health parameter shifts can not be uniquely determined [3.10]. The problem is further complicated by estimation errors due to model mismatch, noise and sensor bias. Sensor validation is an integral part of on-board condition monitoring.
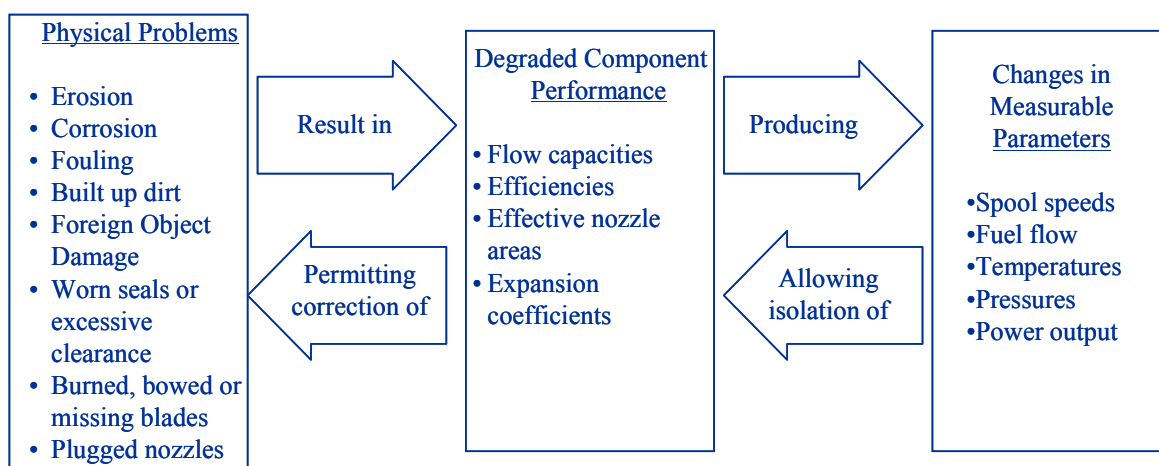
Figure 3.7: Diagram Indicating Information Flow for Turbine Engine Gas Path Diagnostics.

As discussed under the Model-Based Control section, the emerging approach to on-board condition monitoring is to use an on-board real-time model to estimate the health and fault status of the engine. When a fault occurs in the engine, a pattern, typically called the signature, occurs in the sensor residuals. The job of the diagnostics algorithm is to detect and identify unique signatures in the residuals (the difference between the sensed value and the model predicted value – see Figure 3.2). The presence of random (e.g. sensor noise) and systematic errors limits the sensitivity of fault detection, i.e. the size of the fault that can be detected.

The random sensor error cannot be eliminated but the systematic errors in the average model can be eliminated if an individual model is employed. This is done using the tracking filter approach discussed in the section above. Reducing the systematic error in the residuals (measured minus model predicted outputs) effectively increases the Signal to Noise Ratio (SNR) of the detection system, where the systematic error is part of the "noise". The increased SNR results in improved detection capability by allowing either greater fault sensitivity through smaller detection thresholds, or lower false alarm rates for existing thresholds.

Fault detection is structured around classical techniques in the signal processing field, e.g. multiple model hypothesis testing (MMHT). Other techniques such as fuzzy logic and neural networks can also be employed, alone or in combination, and their results fused [3.3]. Specifically, for the MMHT case, fault detection decisions result from Bayesian probability computations based on maximum likelihood considerations applied to the residuals, and from any a-priori reliability information available. The residuals represent information from multiple locations throughout the engine, and fusion of the information is accomplished through use of multi-variate likelihood functions.

Fault isolation is achieved by extending the above fault detection technique to a whole set of specific engine fault candidates through a multiple model hypothesis test structure [3.11]. Figure 3.8 illustrates the MMHT

algorithm with a one-dimensional (i.e. one sensor) example, where L_i is the likelihood of the residual, Δ, given fault i, S_i is the signature of fault i and $prob_i$ is the probability of fault i given the observed residual, Δ.
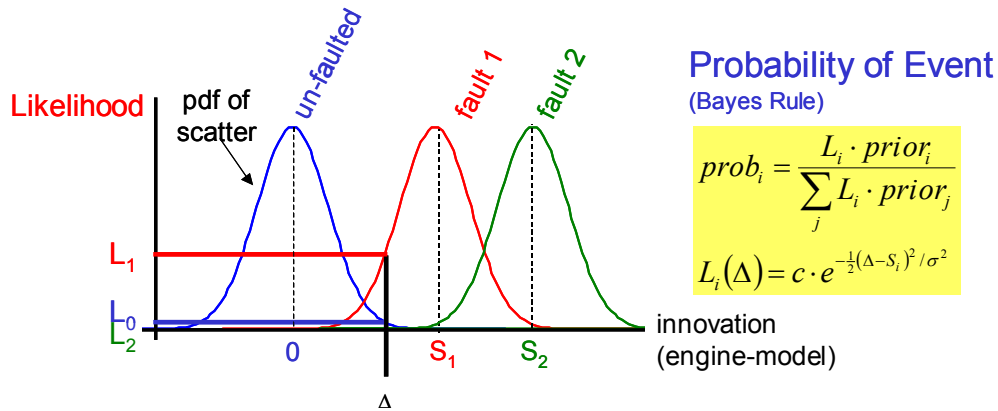
Figure 3.8: MMHT – 1-D Example.

Generally, this requires a model of the unfaulted engine, and one for *each* candidate engine fault to generate residuals for each candidate hypothesis (no fault, and each fault). The ensemble mean of the residuals for each fault model, when run on an unfaulted engine, define the physics based fault signature of each particular fault. Under steady state conditions, the individual fault signatures are constant offsets from the no fault signature, leading to a simplified implementation running just the unfaulted engine model. The residuals for the faulted models are formed by adding the precomputed signatures to the unfaulted residuals. Similar techniques exist to simplify the implementation when the assumption of steady state is not valid [3.11] although in practice the steady-state signatures are often applied transiently.

The personalization of each engine model provides estimates of model parameters that are directly related to the health (e.g. deterioration) of the individual engine components. This information is monitored over time to assess the condition of each component, and can be used to optimize work scope. Figure 3.9 shows an example of trending the tracked parameters for a typical commercial engine.
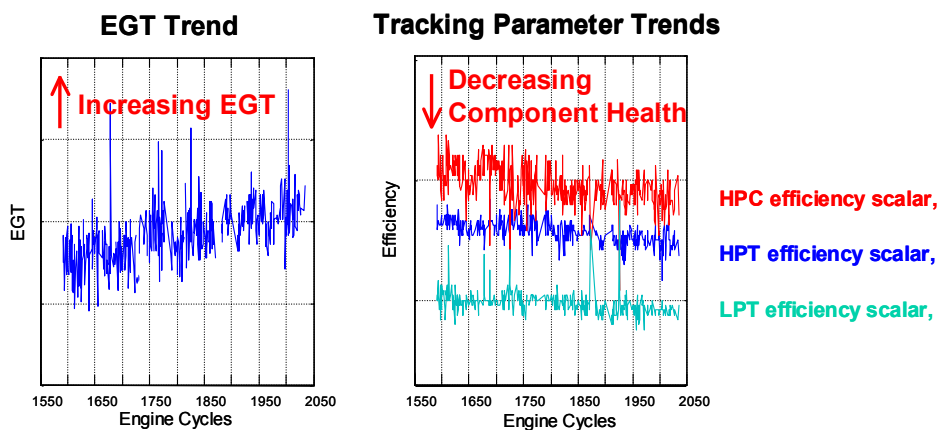
Figure 3.9: Example of Trending Tracked Parameters.

As discussed in Ref. [3.12], a gas path fault might consist of one or more of the following: sensor fault, actuator fault or component fault. The on-board condition monitoring system should not only be able to detect a fault, but also isolate the fault so that appropriate action might be taken. If the effect of the fault on engine operability and/or safety is small, no accommodation is required and maintenance can be scheduled appropriately. However if the fault has an appreciable effect, then accommodation can potentially avoid in-flight shut downs, stalls, excessive life consumption, etc. [3.13] [3.14]. The accommodation strategy is unique for each fault but typically grouped into three main categories, sensor faults, actuator faults and gas path component faults. In addition the strategy is dependent on the control architecture.

Sensor Fault Accommodation: Sensor accommodation is the easiest to accomplish. Once the fault is detected, feedback can be switched to a redundant sensor. This can be either a physically redundant sensor, as in the case of duplex or greater redundancy, or a virtual sensor generated by the on-board model through analytic redundancy. In some cases the virtual sensor may have less accuracy than the physical sensor and some accommodation will be required such as changing control laws and schedules.

Actuator Fault Accommodation: The specific action required to accommodate a failed actuator depends not only on which actuator has failed but also on the specific failure mode. For example, if a VGV (Variable Guide Vane) is failed full open, it may not be possible to run the engine above idle while maintaining operability. But if it fails to some other position, it may be possible to keep the engine running by modifying the engine operation (e.g. changing constraints and opening the bleed valve) – of course some compromise in performance will likely be required.

Gas Path Component Fault Accommodation: Gas path component fault accommodation is more involved than the other two categories. The components are typically large, complex systems, which may operate reasonably well in the presence of the fault, due to closed loop control. Control architecture changes would likely be required when accommodation is necessary. However, the highly nonlinear nature of the engine controller and the complexity of its implementation make the task non-trivial. In addition many diverse requirements exist; maintaining stall margins above certain limits, minimizing both peak temperatures and the time spent above a certain temperature, and obtaining short response times to changes in demand values – all of which must be met over a wide range of flight conditions and disturbance inputs.

Although the focus of this discussion has been on gas path diagnostics, an important part of engine condition monitoring is using vibration diagnostics to determine the structural health of the engine components [3.1]. Increases in vibration amplitude over time might indicate a change in rotor balance related to, for instance, a damaged fan blade or a bearing failure. The low sample rate of current vibration measurements essentially preclude using a real-time diagnostic tool, but many possibilities will be opened up when high frequency measurements become available along with on-board signal processing.

3.4   ADAPTIVE CONTROL

The traditional engine control logic consists of a fixed set of control gains developed using an average model of the engine. Having an on-board engine model which "adapts" to the condition of the engine, opens up the possibility of adapting the control logic to maintain desired performance in the presence of engine degradation or to accommodate any faults in a way such as to maintain optimal performance or trade-off performance with remaining useful on-wing life of the engine. An emerging technique for such an adaptive engine control is the Model Predictive Control (MPC) approach. MPC solves a constrained optimization problem online to obtain the "best" control action, based on a tracked engine model, constraints, and the desired optimization objective.

The ability to account for the constraints explicitly in the controller design is a key benefit of MPC in contrast with other control algorithms, and allows addressing key engine operability and safety constraints directly; e.g. speed and temperature limits, stall margin limits. Also, these constraints can be easily modified for increased/decreased conservatism, based on the operation mode or during a fault. Moreover, since MPC solves an optimization problem online, the optimization objective can be modified based on the operation mode; e.g. minimize fuel consumption during cruise, minimized turbine temperature for increased life, minimized emissions, etc.

Figure 3.10 shows the overall approach for MPC. At each time sample, the nonlinear engine model is linearized about the current operating point, and the resulting linear state-space model is used to formulate and solve a finite-horizon constrained optimization problem. In this way, we obtain the optimal control profile $u_k,...,u_{k+n}$, while enforcing all input and output constraints over the horizon. However, only the first sample of this optimal control profile (i.e. u_k) is implemented, and the whole process is repeated at the next time sample with correspondingly shifted control/prediction horizons.
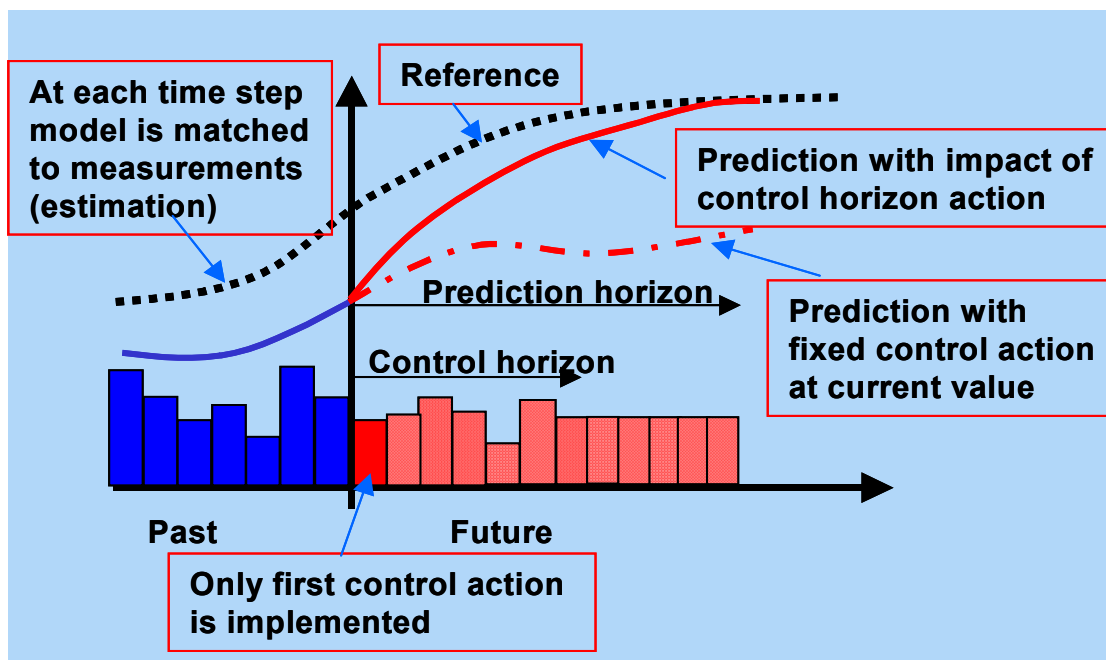
Figure 3.10: Example of Trending Tracked Parameters.

Figure 3.11 demonstrates the kind of performance improvements that a MPC based MIMO controller can provide over a traditional SISO engine control. The figure shows time responses for an engine controlled by a SISO controller (the current FADEC) and by a MPC, during an idle-takeoff transient. We zoom in on some key variables – exhaust temperature, turbine temperature, fuel flow – and notice substantial peak reductions in all of them, which translate into extended engine life. The improvement comes mainly from the fact that the current FADEC is in essence a SISO controller, which drives fuel flow ignoring the interaction between all actuators. The MPC, on the other hand, is multivariable and thus accounts for the interaction between multiple engine actuators and avoids the overshoot in fuel flow. The actuators used by the MPC are fuel flow, VSV, and bleed-valve. More details on applications of MPC to jet engines are available in the literature [3.1] [3.15].
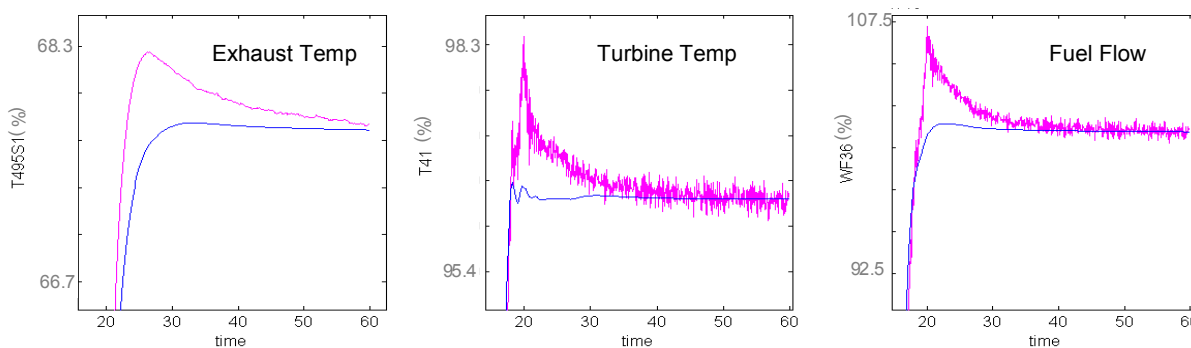
Figure 3.11: Improvements of MPC-MIMO Controller over SISO Controller for Idle-Takeoff Transient. Reduction in peak temperatures extends engine life. SISO actuator is fuel flow, MIMO actuators are fuel flow, VSV, and bleed-valve. Figure shows FADEC/SISO (magenta) vs. MPC/MIMO (blue).

3.5   CHALLENGES AND SENSOR NEEDS

Challenges exist in several areas in implementing the technologies described above. The models must be computationally efficient in order to run in real time without sacrificing accuracy. Sufficient model accuracy is critical in achieving performance enhancement. However, model error is difficult to quantify because it must be evaluated in close loop (i.e. with the tracking filter) which couples it with the choice of tracked parameters and their observability with the given sensor suite. This creates a sensor paradigm shift where sensors are chosen not only for direct control purposes but also for model accuracy, virtual sensors, etc. Equally important is the fault model or signature as it limits the sensitivity of fault detection. Finally the increased complexity brings certification and maintenance challenges. Any engine models used inside the control loops will need to be certified. The complexity of the models and adaptive nature of the tracking filter adds to the challenge. In addition the required model accuracy may necessitate a finer distinction of engine variants in the control software resulting in increased software complexity.

To fully exploit the benefits of model-based control and diagnostics, new sensors can be added. Sensors should be chosen not just for direct use as feedback in the controller but to improve model accuracy, reliability and enhance observability of virtual sensors. Ref. [3.16] provides an excellent summary of sensor needs for intelligent control and health monitoring of aircraft engines. As discussed in Ref. [3.16], structural health monitoring is an important aspect of engine condition monitoring, and there is a need for new and improved vibration and oil monitoring sensors. However, the focus of this chapter is on on-board condition monitoring using gas path information, so only the sensors that are needed for improved gas path diagnostics and engine control are discussed in the following. Since vibration monitoring can be used for indirect gas path diagnostics it will be included in the following discussions.

Typical gas path sensors consist of temperature, pressure and rotor speed measurements. Any improvements in the accuracy, uniformity and reliability of these gas path sensors will result in a direct improvement in the accuracy of performance diagnostics and model-based control technologies. Also, there are currently stations within the engine gas path that are not instrumented due in part to the harsh operating temperatures that exist at these locations. Measurements at these additional locations will further enhance the accuracy of gas path analysis techniques. In addition to conventional gas path pressure and temperature measurements, the ability to sense additional parameters would be beneficial in diagnosing engine performance faults and providing improved estimate of unmeasured variables such as thrust. For example gas path debris monitoring sensors for

monitoring and quantifying engine debris ingestion and discharge are desirable. Additional requirements for improved and new sensors are discussed in the following for vibration monitoring, measurement of air mass flow and fuel properties, and monitoring of exhaust gas composition.

Vibration Monitoring. The primary moving parts of turbine engines are the rotors and their shafts which spin at high speed within the engine case. The elements of these rotors, particularly the fan, compressor and turbine blades, are subject to wear and damage. Such wear and damage may unbalance rotor causing cyclic stress on the structure, engine bearings, engine parts and accessories. Engine vibration monitoring (EVM) systems monitor the level of vibration generated by such rotor unbalance.

The vibration measured by vibration transducers and afterwards processed by engine vibration monitoring unit contains additional diagnostic information about engine elements including bearings, transmissions, reduction gears, fan, compressor, afterburner and turbine and the availability of high speed digital signal processing made it practical to provide very sophisticated vibration analysis in on-board EVM systems.

Some examples of fan, compressor and turbine failures which may be detected by EVM system include [3.17]:

- Partial failure (loss) of turbine and/or compressor blades.

- Blade tip rubs and spacer ring frottage.

- Lockup of fan blade clappers (or mid-span shrouds) and general fan unbalance caused by foreign object damage.

- Shaft coupling misalignment and loosening of compressor stack retaining bolts.

- Blade locking plate misplacement.

Measurement of Mass Flow and Energy Properties. Sensors to estimate the flow through the fan duct and the nozzle will help generate better estimates of the thrust being produced by the engine – especially if there is any damage which results in degraded engine performance. The energy flow to engine can be calculated by multiplication of fuel mass flow and specific heating value of the delivered fuel. Such energy flow sensor can use separate measurement of fuel flow, temperature, density and heating value. The necessary calculation of energy flow can be performed in the EEC by the sensor performing local calculation of the energy flow. The challenge is in measurement of specific heating value for broad range of primary and emergency fuels with additives, contaminants and water that the fuel can contain.

Monitoring of Exhaust Gas Composition. Flames in gas turbine combustor and afterburner emit optical "signatures" that reflect chemistry of combustion process. The radiant emission energy from a combustor is collected by the optical viewing port and transmitted to the electro-optical sensors via the fiber optic cable. Compounds in combustion process emit distinct "lines" in photonic wavelength spectrum. Optical spectroscopy can identify chemical constituents in flame in visible, ultraviolet and infrared spectrum ranges. Technology of optical spectroscopy potentially could be applied to assess bad starts and propagation of flame into turbine, calculate temperature at combustor outlet/turbine inlet (avg. and hot spots), assess degradation due to fuel and inlet air contamination, real time emission monitoring and minimization (through potential development of an active emissions control system), and control instabilities/oscillations (by providing instability detection within an emissions control system).

The requirements/capabilities for the advanced sensors to enable different aspects of Intelligent Control and Health Monitoring for the various engine components are summarized in Table 3.1.

Table 3.1: Sensor Requirements for Intelligent Control and Health Monitoring

Component	Technology	Sensed Variable	Range/Requirements
Inlet	Stall margin management	Pressure	0 – 25 psi range; +-.25% accuracy; 500 Hz bandwidth
			Array of inlet static pressure sensors
Fan/Compressor	Thrust estimation	Flow	1.75% accuracy
Fan/Compressor	Thrust estimation	Torque	10.000 – 20,000 Nm, 10 Hz
Fan/Compressor	Vibration monitoring	Accelerometer	3%, 40 kHz, 1000g range
Combustor	Model predictive control and thrust	Fuel mass flow	± 0,1 % of actual value [kg/s] or [m3/s]
Combustor	Energy flow	Fuel properties	± 0,5 % of actual value [kJ/s]
		Fuel density	± 0,1 % [kg/m3]
Turbine	Clearance management	Clearance	2.5 mm range, accuracy 25 μm, 50 kHz bandwidth
			case-mounted installation
Turbine	Condition monitoring	Accelerometer	3%, 40 kHz, 1000g range
Turbine	Life management/temperature margin management	Temperature	T41, T4B, 5 degrees, 2 – 10 Hz, flow and blade temperature
Nozzle	Exhaust gas composition	NOx, Cox	1%

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Chapter 4 – DISTRIBUTED CONTROL ARCHITECTURE FOR GAS TURBINE ENGINE

by

Dennis Culley and Sanjay Garg (NASA Glenn Research Center)

ABSTRACT

The transformation of engine control systems from centralized to distributed architecture is both necessary and enabling for future aeropropulsion applications. The continued growth of adaptive control applications and the trend to smaller, light weight cores is a counter influence on the weight and volume of control system hardware. A distributed engine control system using high temperature electronics and open systems communications will reverse the growing trend of control system weight ratio to total engine weight and also be a major factor in decreasing overall cost of ownership for aeropropulsion systems. The implementation of distributed engine control is not without significant challenges. There are the needs for high temperature electronics, development of simple, robust communications, and power supply for the on-board electronics.

4.1   INTRODUCTION

Historically turbine engine performance has largely been determined by aero-mechanical innovations. Control systems, although critical to engine operation, have been designed to implement engine functionality rather than be a driving force behind their performance. This is a result of the natural incremental progression of technology which has seen controls evolve from complex mechanisms to the present day Full Authority Digital Engine Control (FADEC). In contrast, the future of enhanced engine performance is generally seen as a highly multidisciplinary endeavor. Advances in materials and design and an increasing reliance on adaptive control will form the basis of improvements in thrust-to-weight ratio and SFC (Specific Fuel Consumption) as well as reduction in environmental concerns like noise and emissions.

As various engine technologies are implemented, there will be additional but not unforeseen pressure on control system design to meet new challenges. In current production engines, controls and accessories (C&A) account for approximately 15 to 20% of total engine weight, an equivalent percentage of acquisition cost, and are a major source of unscheduled maintenance. With the advent of new technologies and all else being equal, C&A will increase its footprint in all three metrics. An example of engine mounted C&A is shown in Figure 4.1.
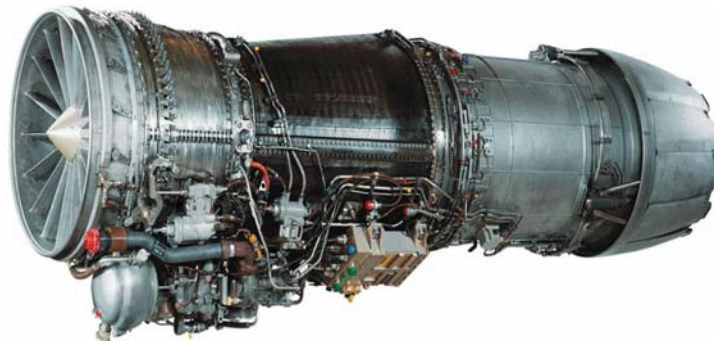
Figure 4.1: Engine Controls and Accessories Comprise a Substantial Portion of Total Engine Weight as Shown in this View of an F414 Engine.

The fundamental response to engine control system design must not be an incremental change but a sea change in system architecture which leverages the substantial gains observed in the electronics and information processing technology industries outside of aeronautics. Moving from centralized engine control architecture to a distributed architecture will be both necessary and enabling for future aero engine design.

4.2 STATE OF THE ART ENGINE CONTROL ARCHITECTURE

Presently, engine control system architecture is based on a centralized design in which discrete sensors and effectors are directly wired to an engine-mounted electronics package. This avionics unit, often known as the FADEC, contains all the necessary circuitry to properly interface with engine control devices as well as cockpit command and data communications. The design of a centralized engine control system is primarily based on the single overriding concern of minimal control system weight because of its effect on overall vehicle performance. Much of the design is based on legacy, the result of incremental improvement over many years. This constraint severely limits the design choices for avionics engineers. The centralized engine control architecture is shown in Figure 4.2.
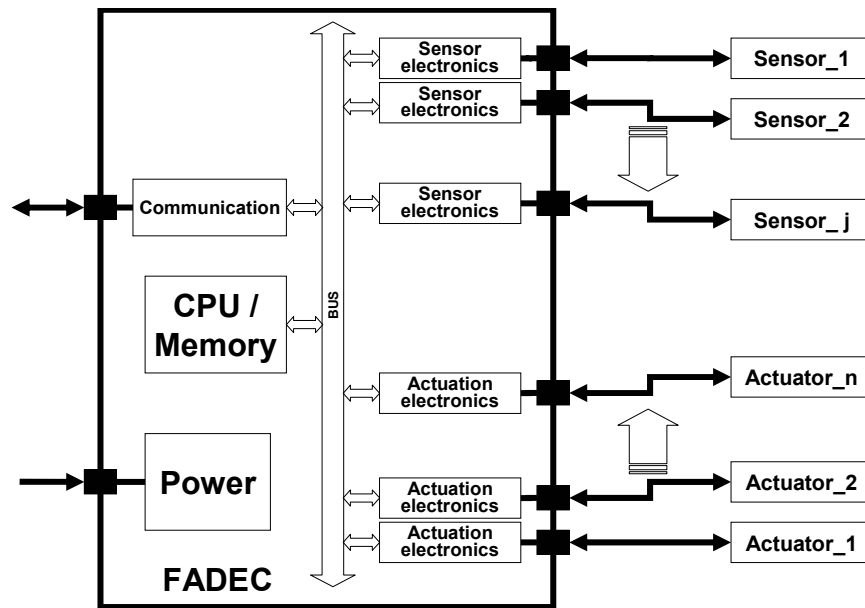
Figure 4.2: Centralized Engine Control Architecture. The FADEC houses specific electronics to interface with engine-mounted control elements (sensors and actuators). Dual redundancy is often used which drives up harness weight while connector size drives enclosure dimensions. The large FADEC housing is environmentally hardened, cooled, and co-located on the engine structure.

In a centralized architecture weight is primarily driven by the quantity and location of control system elements. Due to these weight restrictions and the limited availability of engine access points, there is a very significant pressure to minimize the number of sensors and effectors. With a limited number of control elements each have to be designed with the utmost reliability and well-understood failure modes. In order to drive element MTBF (Mean Time Between Failure) to an acceptable level, dual-redundancy is often used. The end result is a very high weight penalty in connecting the control element to the FADEC due to the number of conductors required and the construction of the wire harness. The weight penalty is minimized by locating the FADEC in near proximity on the engine structure.

The engine structure is quite a severe environment for an avionics package. Vibration and temperature extremes force the electronics to be custom designed for a specific engine. Circuit components are specifically designed for maximum density to achieve small physical size thereby increasing stiffness and raising the natural frequency of resonant mechanical vibration modes. This adversely affects heat dissipation in the assembly. The large number of conductors and the physical size of the connector shells mounted on the FADEC enclosure often drive the package dimensions. The entire package must be mounted on low frequency isolators to reduce the shock loads experienced over a mission profile. Examples of typical FADECs are shown in Figure 4.3.

Figure 4.3: FADEC Examples from the F414 and CFM56 Engines. Note the highly ruggedized packaging, closely spaced I/O connectors, and heavy isolation mounts which all contribute to C&A weight.

Temperature extremes at the engine structure require cooling to reduce the operating temperature of semiconductor junctions to an acceptable level. This is maintained by conduction cooling the entire assembly with a cold plate using the aircraft fuel supply as the heat removal media.

Under a centralized engine control system architecture, the need to reduce overall weight drives a chain of design constraints which result in an optimized engine control system, but one which is costly to both procure and maintain. Furthermore, because it is so highly optimized, it is inflexible to use in multiple platforms or even to accommodate upgrades in an existing application. Changing the engine control architecture to a distributed system can radically alter the interrelated chain of constraints which ultimately drive overall cost of ownership.

4.3   TOWARD DISTRIBUTED ENGINE CONTROL ARCHITECTURE

In a distributed engine control system architecture, as shown in Figure 4.4, any number of control elements are tied together through a common, standardized, communication interface. Sensors and effectors are replaced by control nodes which may provide sensor data, operate actuators, or perform combinations of both. The massive wiring harness which previously tied together the control element to interface circuitry in the engine-mounted avionics package is replaced by a simple but robust communication structure. Weight reduction is the primary motivation but the standardized interface is also an enabling feature which is necessary to effectively implement future adaptive control applications [4.1].
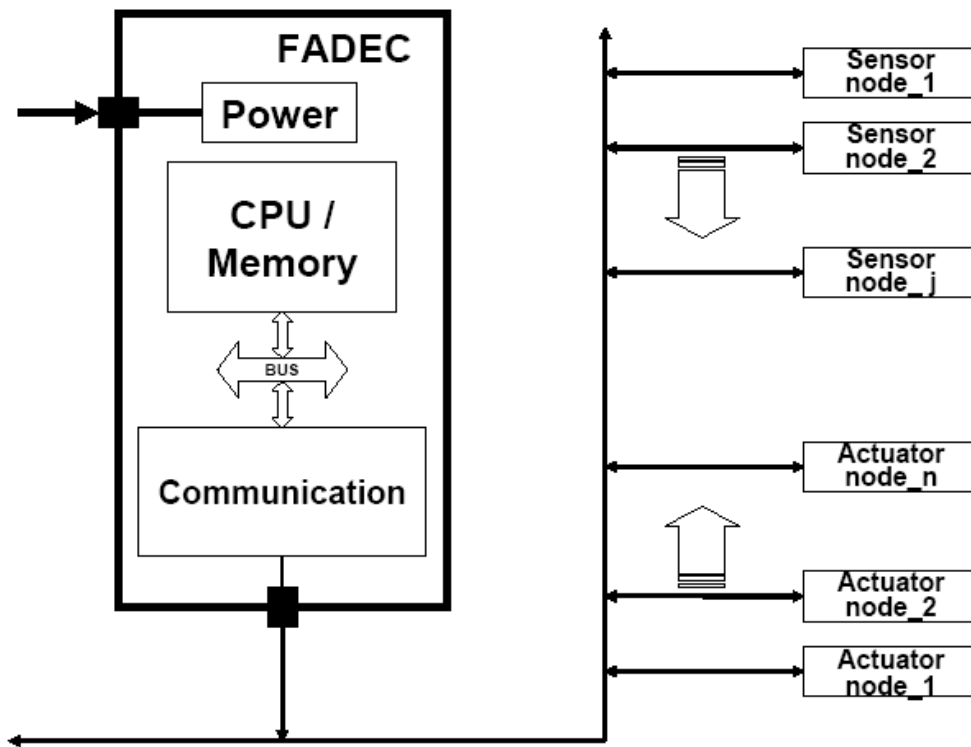
Figure 4.4: Distributed Engine Control Architecture. The FADEC is significantly reduced in size and located in a less severe environment because of a standardized network communications interface. System effectors, however, require intelligence to communicate over the network using a standard protocol. Harnessing weight no longer constrains the system design and the open communication architecture enables simplified expansion.

Control nodes in a distributed control system architecture are by definition "intelligent." Sensor nodes produce information about the physical state of the engine using a predefined data structure. This could take the form of a stream of temporal data in engineering units or a preprocessed state of an engine function, e.g. "impending stall." Similarly, actuator nodes receive commands and/or data from one or more sources to intelligently operate an engine actuator at its most efficient configuration.

In some instances, especially in new adaptive control applications like stall avoidance, high bandwidth, high response control may require nested control nodes which perform both sensing and actuation beneath the overall control communication structure. This is shown in Figure 4.5.
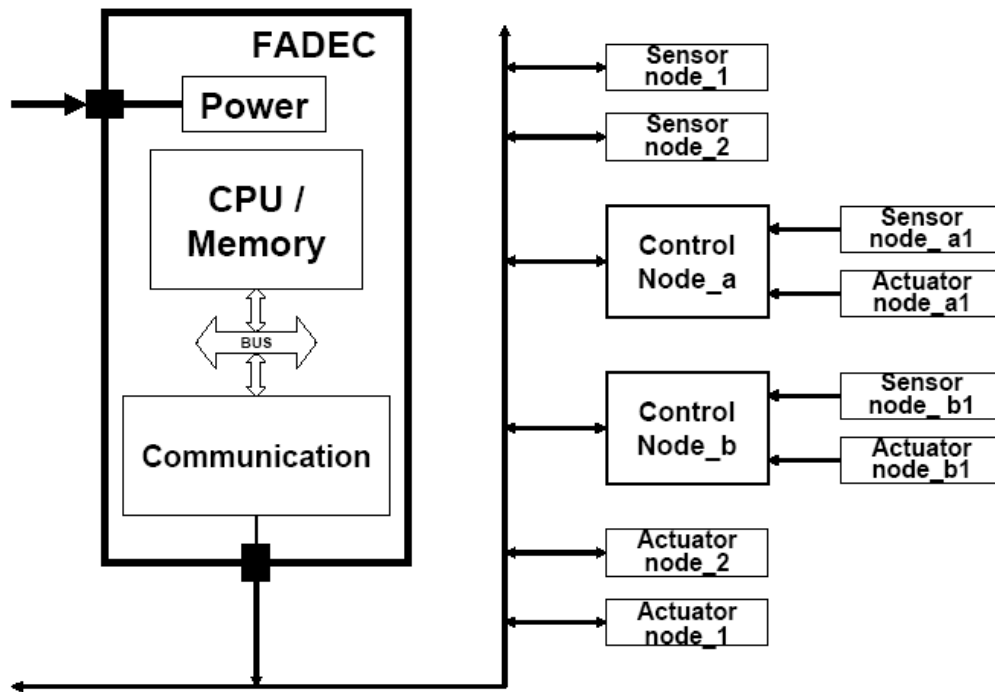
Figure 4.5: Extended Distributed Engine Control Architecture. The open network communication architecture does not constrain the function of the control element. Intelligent nested sub-loops enable the implementation of advanced adaptive control subsystems which may operate at significantly higher internal data rates.

The overall system control is still coordinated by the FADEC which is now physically much smaller. Its function becomes one of processing and communications. Since the communication network is standardized there is no longer a need for unique interface and signal conditioning circuitry for each control element. The number of conductors in each wiring harness and the connector shells do not dictate the avionics package configuration. The location of the FADEC is no longer critical allowing the most complex electronics hardware to be relocated in a more benign environment.

In a distributed engine control architecture weight optimization no longer drives the design and packaging of the FADEC. This leads to broad cross platform standardization and significant cost reductions in both acquisition and maintenance. The issue of system upgrade becomes one largely focused on software re-qualification instead of complete system re-qualification.

4.4   TECHNOLOGY CHALLENGES FOR DISTRIBUTED ENGINE CONTROL ARCHITECTURE

The implementation of distributed engine control is not without significant challenges and there are two "tall poles." These are the need for high temperature electronics and the development of simple, robust communications.

A substantial portion of weight incurred in centralized control was for packaging and cooling of the large avionics assembly. Although the FADEC has been relocated to a less hazardous environment the advent of intelligent control nodes implies that some electronic circuitry has been left behind to handle signal conditioning

and application specific processing functions at the node. These engine mounted components must be able to withstand the temperature and vibration extremes of the environment.

In many cases the temperature requirements will be even more extreme than those previously experienced by an engine mounted FADEC package due to the proximity of the node to the engine components. Recalling that weight is the overriding constraint, the electronics must be able to survive without the benefit of a cooling system. The location of the node will dictate the operating temperature requirement which in some cases could be as high as 500°C.

Standard silicon technology requires a junction temperature of less than 125°C for reliable operation. The capability of the electronic assembly to dissipate heat at the junction is highly design dependent but drives the ambient operating temperature to significantly lower levels, typically 70 to 85 °C maximum. Newer technologies such as silicon on insulator, and potentially silicon carbide, are increasing the design envelope but are still far short of achieving the desired operating temperatures to realize maximum weight reduction. In the absence of sufficient temperature capability, distributed architecture could still be implemented but with a weight penalty for additional structure to minimize heat soak from the engine.

By parsing the bulk of the electronics hardware to the control nodes the physical size of the FADEC package is greatly reduced although there are now more packages over the engine structure. By nature the smaller physical outline causes a shift in the mechanical resonant modes to higher frequencies. This inherently reduces the fatigue issue associated with vibration-excited resonance. Shock loads are still accommodated with isolators but the overall assembly weight is effectively reduced.

The second tall pole is communications. A communication network replaces the heavy point-to-point wiring harness which is a major contributor to system weight in a centralized control scheme. To be effective, communications must not only be reliable but must also be physically simple in terms of connecting nodes. It is imperative that the communication network be based on open system standards to achieve maximum flexibility and lower cost. An example of networked sensors suitable for distributed control is provided in Ref. [4.2].

It may be unlikely that one physical communication medium serves all purposes. Several concepts which are promising include wireless technology, fiber-optics, and communication over power distribution wires. Even though several physical layer media may be used in the actual implementation of distributed control it should be of minor significance in the effectiveness of the communication network.

NASA Glenn Research Center in conjunction with members of the U.S. (United States) Department of Defense and the U.S. Aerospace industry has established a Distributed Engine Control Working Group (DECWG) to examine the current and future technology requirements to enable distributed control for aircraft engines. The work of this group to date in terms of assessing the paradigm shift from centralized engine control architecture to an architecture based on distributed control using open system standards is summarized in Ref. [4.3]. This reference also provides a summary of the work being done in distributed engine control technology development since the 1990s.

4.5   ADDITIONAL BENEFITS OF DISTRIBUTED ENGINE CONTROL ARCHITECTURE

The modular, open system model for distributed engine control has additional benefits which will surely be exploited for cost savings, system reliability, and performance. Integrated Vehicle Health Management

(IVHM) will become more pervasive as embedded intelligence becomes the norm in each control node. Each sensor and actuator would be designed with built in test modes which perform local diagnostics at startup or during flight at the request of the FADEC or pilot. Self-calibration could, in many instances, be incorporated which would increase the accuracy of system data and improve overall performance. Finally, trend analysis could be used to track the degradation of systems and components leading to reduced maintenance cost by eliminating unnecessary scheduled tear downs.

Due to the open architecture diagnostics can be performed on several levels beginning at the local nodes and progressing over the entire system. In fact, diagnostic modules could be inserted anywhere, passively listening to the network traffic and evaluating conditions without impacting the system control.

Distributed systems also open up the possibility of more closely coupled engine/airframe systems. Assuming airframe sensing and actuation follow the same architecture then the engine and airframe are just extensions of the same control system. The engines, viewed in this mode, could even be considered as airframe actuators assisting in vehicle maneuvers.

4.6 SUMMARY

The transformation of engine control systems from centralized to distributed architecture is both necessary and enabling for future aeropropulsion applications. The continued growth of adaptive control applications and the trend to smaller, light weight cores is a counter influence on the weight and volume of control system hardware. A distributed engine control system using high temperature electronics and open systems communications will reverse the growing trend of control system weight ratio to total engine weight and also be a major factor in decreasing overall cost of ownership for aeropropulsion systems.

It is important to note that no new sensors or actuators are needed to enable distributed engine control. What is needed is to have on-board electronics located on or close to the sensing element or the actuator effector such that network communications can be enabled and the wiring harness required for communications between sensors and actuators and the engine controller can be substantially reduced. Another challenge for enabling distributed engine control is to supply the power needed for the on-board electronics – innovative power supply architectures and technologies will need to be developed to exploit the full potential benefits of distributed engine control.

4.7 REFERENCES

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Chapter 5 – UNIVERSAL SENSOR AND ACTUATOR REQUIREMENTS

by

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5.1 INTRODUCTION

The previous chapters have focused on the requirements for sensors and actuators for "More Intelligent Gas Turbine Engines" from the perspective of performance and operating environment. Even if a technology is available, which meets these performance requirements, there are still various hurdles to be overcome for the technology to transition into a real engine. Such requirements relate to TRL (Technology Readiness Level), durability, reliability, volume, weight, cost, etc. This chapter provides an overview of such universal requirements which any sensor or actuator technology will have to meet before it can be implemented on a product. The objective here is to help educate the researchers or technology developers on the extensive process that the technology has to go through beyond just meeting performance requirements. The hope is that such knowledge will help the technology developers as well as decision makers to prevent wasteful investment in developing solutions to performance requirements, which have no potential to meet the "universal" requirements. These "universal" requirements can be divided into 2 broad areas:

1) Technology value proposition; and

2) Technology maturation.

These requirements are briefly discussed in the following.

5.2 TECHNOLOGY VALUE PROPOSITION

A fundamental premise (beyond basic safety) for considering the incorporation of any component onto/into the engine is that it adds value. Some components will be considered intrinsic to the engine design and functionality (e.g. engine control, fuel system components, cycle temperature sensors), and as a result, their value is tied directly to the overall product's attributes (fuel burn, range, direct maintenance cost). All other non-intrinsic components added to the engine are required to provide some level of value that, at a minimum, mitigates the negative effects of its installation (weight, volume, energy consumption, installed losses).

In the best case, the value added will provide direct positive impact to the customer in terms of increased revenue opportunities, or via easily measured life-cycle cost reductions. But this does not always have to be the case. Value can also be gained via non-direct cost reductions for the customer, and often the OEM (Original Equipment Manufacturer) of the engine or aircraft most easily captures the value. In these cases, it is generally assumed that this value can be passed on to the customer in some fashion, in whole or in part.

One common way that value analysis is performed is via a calculation of customer net present value (NPV). This common metric allows for capture of the life cycle costs and benefits of the proposed component or feature. Typical evaluation elements include (but are not limited to) the following:

Impact on Revenue: Does the technology provide enhanced utilization rates, increased dispatch reliability, increased ETOPS (Extended-range Twin-engine Operational Performance Standards) availability, or performance improvement? Is the technology a performance enabler? If the answers to any of these value adding objectives is yes, then an assessment has to be made as to what impact will this technology have on the customer's revenue stream – how much can the revenue be increased over the life-cycle of the technology. Typically, sensors or actuators are part of an overall control or diagnostic technology. So the revenue impact has to be considered for the technology as a whole, and the value of the sensor or actuator has to be determined from its criticality for enabling the technology.

Impact on Cost: Any new technology impacts the cost to the customer in various ways. The first impact is the acquisition cost. How much will the cost of the engine go up if the technology were to be incorporated into the engine? The acquisition cost has to account for factors such as the non-recurring engineering development cost, recurring costs associated with buying the particular sensor/actuator from a vendor, cost of integrating the sensor/actuator into the engine, cost of spares, etc. Another important element of cost is that associated with maintenance. The reliability of the sensor/actuator and its impact on events such as aborted take-off, inflight engine shut-down, and aircraft diversions have a big influence on the operational costs of incorporating the technology. The labor and time cost associated with part removal, line maintenance, shop maintenance, repair, troubleshooting have to be factored in when calculating the overall impact of the technology on the life cycle cost of the engine.

Other: Other than revenue and cost, some other factors to be considered for sensors and actuators are impact on overall engine weight, the capability of the technology to fit into the specified volume (since real estate on an engine is at a premium), accessibility once installed onto/into the engine, cooling requirements, power and wiring requirements. Designing for ease of integration into the engine has to be an important element of developing any technology solutions to challenging sensor/actuator performance requirements.

5.3 TECHNOLOGY MATURATION

The process of moving a product, process or component towards maturity typically follows the development route as described in the Technology Readiness Level (TRL) definitions [5.1]. Business, manufacturing, legislative, etc., issues must be covered at an appropriate level at all stages.

The process typically follows a gated process involving formal reviews at specific stages, generally related to specific TRLs.

Any work within a business must have a business case, although up to TRL3 (proof of concept) this may be fairly loose. The level of investment will reflect the level of associated risk. The typical correlation is that at low TRLs, the risk is relatively high, so low levels of funding will be used in simple evaluations of the technical and business risks. As the TRL level increases, the level of understanding should rise and the level of risk should fall. Achievement of the higher TRLs inevitably requires much higher investment, although this is typically achieved with a much clearer business case and lower risk.

A gated review process is typically used to monitor and control the development and risk mitigation. Major formal reviews may be undertaken after TRL4 has been achieved, i.e. the component and/or system has been validated in a laboratory environment. At this stage, the basic technology will have been formulated together with the preferred embodiment as a practical device and the operational, business, etc., benefits should have been evaluated. This will provide a good prediction of the final implementation.

A higher investment will typically be needed to reach TRL6 (system/subsystem model or prototype demonstration in a relevant environment). After this, the concept will be expected to be suitable for design into a development product. The development gate at TRL6 will typically provide this final decision of whether to continue to product development and will have a much more rigorous business and application evaluation.

Once established as a product at TRL9 (actual system proven through successful mission operation), the system will be ready to enter routine service. Periodic reviews of the system are likely to continue throughout it's service life.

5.4   REFERENCE

[5.1]   Appendix 1 – RTB Endorsed Proposed NATO Hardware TRL Definitions (24 September 2007).

Chapter 6 – SENSOR REQUIREMENTS AND ROADMAPS

by

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ABSTRACT

The chapter starts with a brief overview of the state-of-the-art of the sensing technologies. Principles of detection and the stage of integration in conjunction with the need are discussed. Based on the projected sensor requirements to accomplish propulsion systems with distributed active control, the existent gaps and selected types of sensor technologies are addressed, which are foreseen to deliver the required sensitivity, the resolution, the range, and the bandwidth in classes of sensors and which will allow operation under harsh environment conditions. By changing the packaging and/or design of the current sensors, operation environments of 750°C may be possible, which would meet requirements for sensors located towards the engine intake, compressor and in some cases low-pressure turbine. However, the majority of sensors for locations close to the engine combustion chamber or afterburner (with operation temperatures up to 1700°C) do not exist. There is also a need for smart sensors, which would enable future distributed control architecture. In addition a number of sensors, which are of interest for more intelligent gas turbine engines, are being explored or do not yet exist, for example turbine emission species sensors, burning patter factor sensors, fuel property sensors, and exhaust gas composition sensors. Meanwhile, rapid emerging technologies were made available during the three years duration of the Task Group. These include tip clearance measurement technologies such as eddy current, and microwave methods. To meet future sensor requirements, new fabrication and material technologies (MEMS, other), advanced sensing principles (spectroscopy, other), and their potential applications to new sensor types need to be explored. The status of current R&D for new sensors and future expectations are summarized in a comprehensive table. Sensors and associated electronics that have to operate in high temperature are foreseen to be largely available by 2015 (SiC) and 2020 (SiCN). Both of these technologies come with the potential of embedding such high temperature sensors within the structure.

The information presented in the chapter represents the state-of-the-art of the sensing technology of the years 2005-2007 to the best knowledge of the authors. The authors are also fully aware of the fact that there may be many ongoing research programs as well as individual research that are not publicly supported and public information is not available. Therefore, the report might miss that section of knowledge. Also, progress in research and development is made every day such that often, the recent information may be fast outdated. The reader should bear in mind these facts.

6.1 INTRODUCTION

Sensing represents one of the vital components of the control schemes with the sensors providing the physical signal to enable the control loop and monitoring of engine condition. Since the reliability of the sensing element is often the lowest link in the control elements, development of appropriate sensor systems is critical to affordable and reliable implementation of the technologies for more intelligent gas turbine engines. The goals for these future engines were discussed in Chapters 2 (active control of engine gas-path components), Chapter 3 (various aspects of intelligent control and condition monitoring) and Chapter 4 (distributed control architecture). In these chapters, components and applications specific performance sensor requirements (such measurement capabilities and operational environments) were described. Additional

non-performance requirements (such as low cost and reliability) that a sensor technology has to meet in order to be considered for implementation on an engine were summarized in Chapter 5.

The different sensor functions impose different requirements for the sensors. For example for controls, sensors have to demonstrate a proven extended reliability, which means that sensor failure is unlikely. For health monitoring, on the other hand, monitoring sensors with less proven reliability can be used given the non-critical role of such sensors. While some of the identified sensors will be available or almost readily available, others sensors require significant research and development efforts.

Sensors development has followed the overlapping between the need of the users and technical capability for the supplier. There have been developments of sensors that have followed a specific requirement imposed by the user. However, such sensors are further used by other industries that find the packaging as suitable. Moreover, a platform of sensors could be used in multiple applications either by changing the packaging or the adjustable features of the system. Besides the temperature sensors, all other sensors are usually built to operate within an environment that corresponds to the temperature limits of the surroundings. Under these circumstances, there are few sensors which could detect for example pressure under high temperature. Even if such sensors exist, they may not satisfy other essential conditions to operate within the propulsion system in flight missions, namely high reliability and reduced mass. The reasonable cost is another aspect to be considered when the selection of a sensor is made.

In the following paragraphs, "high temperature" means a temperature regime at which sections of the gas turbine engine operate (as per the table of Chapter 2) and for which practical sensors do not exist to measure the necessary physical quantities to enable the implementation of adaptive distributed control on the future more intelligent gas turbine engine.

The need for new sensor technology for more intelligent gas turbine engines is indirectly addressed by several national and European programs and organizations, although they are mainly directed towards enhanced performance and environment friendliness. Such programs yield through the supported projects the significant advancements in the instrumentation of the propulsion systems. Examples include the VAATE (Versatile Variable Advanced Turbine Engines) program – US Air Force; Advanced Technology Program (embedding of sensors for example) – UK Defense Evaluation and Research Agency (DERA); and the **Adv**anced **Act**uation Concepts (ADVACT) Program – EU. Also, organizations have been established to address future GTE technologies, including the Propulsion Instrumentation Working Group (PIWG) in the US and the Advisory Council for Aeronautics Research in Europe (ACARE). European Commission co-funds technology programs that are targeted to achieve ACARE 2020 goals, including emission and noise pollution reductions. Such programs are within scope of the Efficient, Environmentally Friendly Aero Engine (EEFAE) program within the EU Framework Program 5 (FP5) and CLEAN and ANTLE and VITAL projects within FP6. Also, the New Aero Engine Core Concepts (NEWAC) project is another FP6 project validating novel technologies enabling reductions in CO_x and NO_x emissions. NASA conducts the UEET program with similar objectives.

This chapter will focus on sensor requirements for more intelligent engines with the objective to identify the status of current and future potential sensing technologies. The following Section 6.2 will define generic requirements covering all sensing variables based on the performance requirements of previous chapters. Section 6.3 will explore which of these requirements can be met with current technologies. Standard sensing principles are briefly summarized and detailed information on current sensors will be described. Section 6.4 will describe new sensing principles and their application to future potential sensors. Microtechnology and new sensing principles represent possible directions for advanced GTE sensors. Section 6.5 attempts to develop roadmaps for these future sensors.

6.2 GENERIC SENSOR REQUIREMENTS

The discussions of current status and future potentials for sensors will be based on generic sensor requirements. For example, for temperature and pressure sensors the generic requirements will be defined by measurement capability (range, bandwidth, resolution, and accuracy) and the capability to withstand certain operation environments (temperature and vibrations), without considering where these sensors are located. In the following, some general comments on current sensors and the need for new sensors are made, before the generic sensor requirements will be addressed in the context of Table 6.1.

Table 6.1: Generic Sensor Requirements

Sensed Varible	Sensor Operation		Application
	Environment	Requirements	
Temperature	700 - 1700°C	± 5°C accuracy, < 1 Hz bandwidth,	Burner patter factor
		resolution 5°C , 0-10 Hz bandwidth	Surface temperature turbine stator; turbine cooling (less than 1 Hz); life extending control (2-10 Hz)
Pressure	15 - 106 kPa, -60°C to +65°C	pres. +3 bar, res. ± 0.1%	Active inlet control
	15 - 106 kPa, -60°C to +65°C	res. ± 0.25%, 500 Hz bandwidth	Inlet distrosion control
	15 - 1800 kPa, -60°C to 500°C	35 kPa dynamic, ± 0.2% resolution, 5 - 40 kHz bandwidth	Stall margin management
	15 - 1800 kPa, -60°C to 700°C		
	15 - 1800 kPa, -60°C to 500°C	35 kPa dynamic, ± 0.5% resolution, 1 Hz bandwidth	Active surge control
	15 - 1800 kPa, -60°C to 700°C		
	300 - 4000 kPa, 700°C to 1700°C	10 kPa dynamic, ± 5% resolution, 1000 Hz bandwidth	Combustion instability suppression
Vibration (accelerometer)	15 - 300 kPa, -60°C to +65°C	3%, 40 kHz, 1000g range	Vibration monitoring fan
	300 - 4000 kPa, 700°C to 1700°C	3%, 40 kHz, 1000g range	Condition monitoring turbine
Emission Species	300 - 4000 kPa, 700°C to 1700°C	COx, NOx, 5% resolution, 5 Hz bandwidth	Emission control
Tip Clearance	15 - 1800 kPa, -60°C to 700°C	2.5 mm range, 25 μm resolution, 50 kHz	Compressor tip clearenece control
	300 - 4000 kPa, 700°C to 1700°C	2.5 mm range, 25 μm resolution, 50 kHz	
Flow	15 - 300 kPa, -60°C to +150°C	1% resolution, 1ml/sec min flow	Thrust estimation
Torque	15 - 300 kPa, -60°C to +150°C	10.000-20,000 Nm, 10 Hz	Thrust estimation
Position/Arrival time	15 - 1800 kPa, -60°C to 700°C	capacitive or inductive, 50 kHz bandwidth, resolution < 0.25mm	Active vibration control
Fuel Flow	300 - 4000 kPa, 700°C to 1700°C	1% resolution, > 6 Hz bandwidth	Mass fuel flow
Fuel Properties	300 - 4000 kPa, 700°C to 1700°C	±0.5% resolution, quasistatic	Energy flow
Exhaust gas composition, COx, NOx	20 - 200 kPa, 300°C - 500°C	resolution ±1%, quasistatic	Condition of the burner

The main type of sensors presently used in GTE for gas path related measurements include sensors for temperature, pressure and differential pressure, RPM, one-per-revolution, torque, vibration, position, and fuel flow measurement. Other sensors, such as oil quantity and oil debris detectors, are outside the scope of the report. The current gas-path sensor types have been known from other quantity based products. Such sensors were designed and packaged according to the specifications driven by the certification requirements to the aircraft and GTE and were mostly written by the GTE manufacturers following guidelines of MIL-STD 810F for tailoring sensors's environmental design and test limits to the conditions that the specific sensor will experience throughout its service life, and for establishing laboratory test methods that replicate the effects of environments on sensors [6.67]. Specifications of most of present sensors with integrated electronics are limited to environment conditions within –65°C to +115°C. Sometimes the temperature limitations can be overcome with integrally attached electronics that is installed in the GTE location with acceptable temperature. The sensors

require very rugged packaging to be able to operate within an environment that corresponds to the temperature limits of the sensor surroundings and locations on the engine and to meet reliability requirements.

By changing the packaging or the adjustable design features of the system (for example distance between sensor and engine wall) some of the current sensors can be modified to meet higher then present operating temperature ranges. Operation environments of 750°C or higher may be possible, which would meet requirements for sensors located towards the engine intake, compressor and in some cases low-pressure turbine. However, even if such sensors exist, they may not satisfy other essential conditions to operate within the propulsion system, including life, time between overhaul, reliability and small volume and mass. Also data processing of these transducers has to be carried out in a low temperature location. For sensor locations closer to the engine combustion chamber or afterburner, sensors withstanding even higher temperatures (up to 1700°C) are needed. With an exception of thermocouples, new sensors and sensors technologies are needed to enable measurements in these "high temperature" regions.

The requirement for sensors capable for operation at high temperatures is substantiated by the goal of distributed control architecture. For this concept smart sensors, which perform measurements, process data and take decision, and provide feedback for actuation at the subsystem level, are required that could operate at higher temperatures than presently possible. In present systems pressure, temperature and rotor speeds sensing elements are distributed across turbine engine systems in order to provide optimal engine control and health management functions throughout the flight envelope and at all stages of engine life. Traditionally these functions are embedded in the full authority digital engine control (FADEC), but preferably they should be distributed to the sensor level, which requires robust intelligent sensing technologies for temperature and/or pressure sensors that can withstand high temperatures and vibration environments present in GTE, particularly those used for sustained high Mach flight. Presently smart or intelligent sensors can be fabricated using silicon (Si) based technologies, which allows integration of sensing and signal processing and electronics at the chip level using the concept of Micro-Electro Mechanical Systems (MEMS) described later. However, since standard Si technology requires a junction temperature of less than 125°C, advanced technologies are required for high-temperature integrated sensors. Therefore it is currently not possible to transfer the processing from the FADEC to the sensing elements. Efforts towards the development of sensors that have been oriented towards the development of the sensors with integral electronic installed in the locations with operating temperatures higher then approximately 100…115°C or cooling is required. Effort will be described later that has been directed towards the development of sensors with integrated processing electronics that will enable the above requirements at temperatures exceeding current rating of military or industrially rated electronic components will be described further.

Implementation of available and future sensors is an additional major issue. Sensors should be small, light, low cost, and reliable. Also embedding of sensors within the structure of the engine is an issue that has been investigated by researchers, but has not been implemented in prototypes or even on military engines. The reduced size of the sensors, possible through application of MEMS or microtechnology, may significantly help, when addressing the above challenging and enhancing the measurement capabilities (for example the bandwidth upper limit for pressure sensors or accelerometers could be significantly improved through miniaturization).

Future GTE operation will in part build on the present sensor types, however operation at higher temperatures and enhanced vibration exposure will be required. Also miniaturization for these sensors is desirable to utilize the advantages of the microsystems, namely low mass, high reliability, redundancy, low energy consumption, and low cost per provided data. In addition, new sensor types are needed for advanced gas turbines for measurements of tip clearance, turbine emission species, air path flow variations, fuel flow, fuel properties, and exhaust gas composition as discussed in Chapter 2 and 3. Depending on their location these sensors require

different measurement capabilities and will be exposed to different environments during their operation. In the following, sensor status and needs will be discussed in generic terms of capability and environmental exposure, without referring to their location in the GTE or referring to specific GTE components.

The specific generic requirements associated with the sensors that are foreseen to be used in future more intelligent propulsion systems are summarized in Table 6.1. For example for temperature and pressure measurements different requirements are identified for environmental exposure and capabilities, such as range, resolution, accuracy, or bandwidth. Similar environmental and capability needs are provided for remaining sensors, identified for future GTE operation. Despite the fact that some of the sensors do not require to face very high temperature environment, they are not available now mainly due to the fact that they have not yet been adapted for implementation, to the best knowledge of the authors, in any GTE. Therefore the capability associated with the flight qualification and/or structural embedding is yet not known at the present time.

6.3   CURRENT TECHNOLOGIES

6.3.1   Current Sensing Principles and Technologies

The sensor technologies presently used in GTE are associated with well-known sensing principles and fine tuned to the present requirements. These current sensing principles relevant to GTE are summarized below and their applications to current GTE sensors are discussed in groups of sensed variables, including temperature, pressure and differential pressure, RPM, one-per-revolution, torque, vibration, position, fuel flow, and flame detection. For some variables, different types of sensors with different sensing principles are available, but they have not been implemented in GTEs. All of sensors in discussion exhibit an electrical output to be further used in the control system.

6.3.1.1   Temperature Measurement

Temperature is measured based on well known physical phenomena. Two dislike metals joined in a point will produce a steady flow of electrons, when the two ends of the thermocouple are set at a difference of temperature (Seebeck Effect). According to the type of materials used in the thermocouple, specific difference of potential is recorded for the same temperature difference. The most accurate temperature detection sensors are the thermo-resistors. The principle of the thermo-resistor is based on the resistance change of a conductor when heated. The increasing temperature increases the electrical resistance in the large majority of metals. Pt is the most common material used for thermo-resistors given its linear dependency of resistance with temperature in a quite large temperature range.

6.3.1.2   Piezoresistive Sensing

The piezoresistive principle is based on resistance modification of a conductor specimen when subjected to strain or elastic deformation. Any elastic restoring element can be instrumented with piezoresistors (strain gages) and used to measure steady or time-variable physical quantities that produce the temporary elastic deformation of the sensing element. Pressure is traditionally measured of this fashion, more recently combined with microtechnology. A drawback of silicon piezoresistivity is its strong dependence on temperature that must be compensated for with external electronics.

6.3.1.3   Piezoelectric Sensing

The piezoelectric phenomenon is created in materials that have a dominant polarization within their intrinsic structure. When subjected to a strain, electrons of the atoms within the structure will be released and create a

charge that can be related to the input quantity. Certain natural crystals exhibit piezoelectric properties and stability under high temperatures ranging up to 750°C. Vibration transducers and accelerometers, using this principle, are commercially available.

6.3.1.4   Capacitive Sensing

Capacitive sensing relies on an external physical parameter changing either the spacing or the dielectric constant between the two plates of a capacitor. The advantages of capacitive sensing are very low power consumption and relatively good stability of the measurement with temperature.

6.3.1.5   Photo-Sensitive Effect

The photo-voltaic phenomenon converts the photon energy that hit the surface of a conditioned material (such as Se) to an electric signal. The photo-sensitive phenomenon could be exploited in many ways for quantitative detection of specific physical quantities. Temperature could be detected by pyrometry which enables color matching of incandescent media with a specimen of known temperature. The method has been extended to analyze arrays of temperature gradients through array pyrometers. Extended beyond the visible spectrum, the Fourier analysis of the spectrum released by a media is at the base of the gas species detection while the interferometry can be used to detect small geometric distortions. Moreover, the interference of coherent light within an optical fiber can be significantly distorted by the physical environment changes such as temperature and pressure. The principle could be used to measure and multiplex the signal transmission such that a unique fiber could be used for a section of the propulsion system. The photo-sensitive methods extend but are not limited to the thermal paints, which witness the peak temperature encountered in a certain section of engine. The photo-sensitive principle is also used in photodiodes and photomultipliers for light detection.

6.3.1.6   Inductive (Electromagnetic) Sensing

The basic principle is related to the inductance change under the provision of position change of the moving element that holds either a ferromagnetic material or an electromagnet. The inductance change could be detected by semiconductor devices such as Hall Effect sensors. The measurement method enables the integration of numerous applications including flow sensing, position detection (for example Linear Variable Differential Transformer (LVDT) and Rotational Variable Differential Transformer (RVDT), position rate, angular velocity, and force and torque measurements. Similar principle could be employed to function under high temperatures.

6.3.1.7   Inertial Measurements

The classical technology for the inertial sensors is based on the mass-spring resonator, which is scaled down at micro-level. The detection of the motion is performed by capacitive or inductive means. Inertial sensors are mainly used to detect the acceleration and the rotation rate. More recent technologies employ the Doppler Effect. This non-contact method, which makes use of a coherent light beam (laser), could be used under very high temperature conditions.

6.3.1.8   Vibrating Element Principle

The principle provides a frequency output for varying conditions and can be applied to pressure sensors or to vibration detection sensors.

6.3.1.9 Magnetic-Optical Detection

The magneto-optical detection utilizes the detection of the magnetic pattern on an optical medium. The measurement principle enables 3-D temperature imaging and has proved to be a good potential in spatial temperature mapping. The principle is also used for position sensors, where applied magnetic field causes a change in light deflection.

6.3.2 Current Sensors

6.3.2.1 Temperature Sensing

6.3.2.1.1 Thermocouples

Thermocouples are the only known self-powered temperature sensors. The voltage provided by the Seebeck effect (see above) varies with temperature and is unique for a given pair of conductor materials and is specified in international standards [6.1]. Thermocouples manufactured to the international standards are fully interchangeable and their performance is independent of the manufacturer or the country of origin.

Table 6.2: Standard Thermocouple Types [6.2]

Type	Commonly Used Names	Temperature Range (ºC)
B	Platinum 30% Rhodium – Platinum 6% Rhodium	0 to 1700
E	Nickel Chromium – Copper Nickel	0 to 850
J	Iron – Copper Nickel	–200 to 750
K	Nickel Chromium – Nickel Aluminium	–180 to 1100
N	Nicrosil – Nisil	–180 to 1100
R	Platinum 13% Rhodium – Platinum	0 to 1500
S	Platinum 10% Rhodium – Platinum	0 to 1500
T	Copper – Copper Nickel	–250 to 370

Thermocouples are designed as individual replaceable probes, integrated thermocouple/cable assemblies or rigid thermocouple rake assemblies. Immersion probes provide specific or averaging of temperatures at multiple immersion depths with resistance balancing for true electrical average and are often dual channel. Thermocouples can be designed with enclosed or exposed junctions depending on the time response requirements. Thermocouple harnesses features either

1) Common junction arrangements, where the resistance of each thermocouple circuit is balanced, eliminating errors due to resistance variation; or

2) Individually wired probes for detailed gas path measurements.

The averaging of thermocouple temperatures is a method commonly used for exhaust temperature systems. Immersion probes often provide temperature and pressure sensing incorporated in the same housing. Typical

accuracy of Type K thermocouple is 0.4% of point above 260°C [6.3]. Thermocouples are typically used for temperature measurement at Exhaust Gas, Compressor Discharge, Bleed Air, Bearings, Oil, Fuel, Inlet Air, T2, T2.95, T3, T4, T4.7 stations.
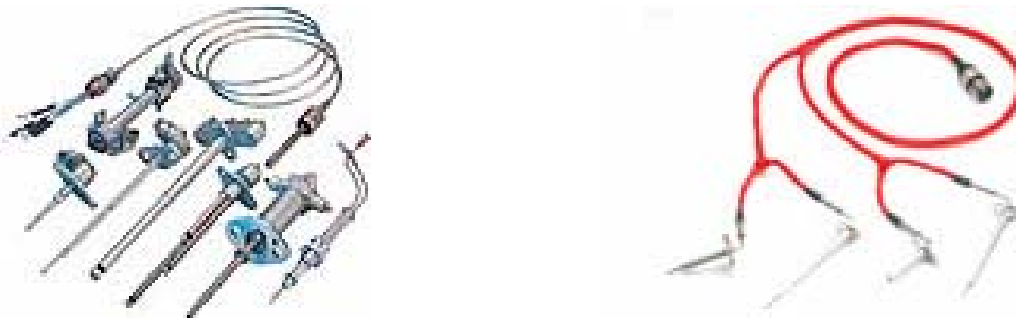
Figure 6.1: Thermocouples of Weston Aerospace [6.2] and Harco [6.4].

6.3.2.1.2 *Resistance Temperature Devices (RTD)*

A RTD operates on the principle of change in electrical resistance in wire as a function of temperature. The most commonly used as detectors are Nickel and Platinum. A typical RTD consists of a fine platinum wire wrapped around a mandrel and covered with a protective coating. Usually, the mandrel and coating are glass or ceramic. Platinum RTDs offer very good long-term stability: e.g. better than 0.1°C per year. Although the Platinum temperature – resistance curve is much more linear than the thermocouple's temperature – voltage curve, for high accuracy temperature readings liberalization of this curve is still needed.

Table 6.3: Standard RTD's Types [6.2]

Type	Commonly Used Names	Temperature Range °C
Nickel	MIL-T-7990	–40 to 400
Platinum	DIN 43760	–40 to 850

In the latest RTDs the Platinum wire has been replaced by a Platinum thin film deposited onto a small flat ceramic substrate, etched with a laser-trimming system and sealed. Due to its small size the device can respond quickly to temperature changes, and is more robust and therefore more suitable for aerospace applications [6.2].
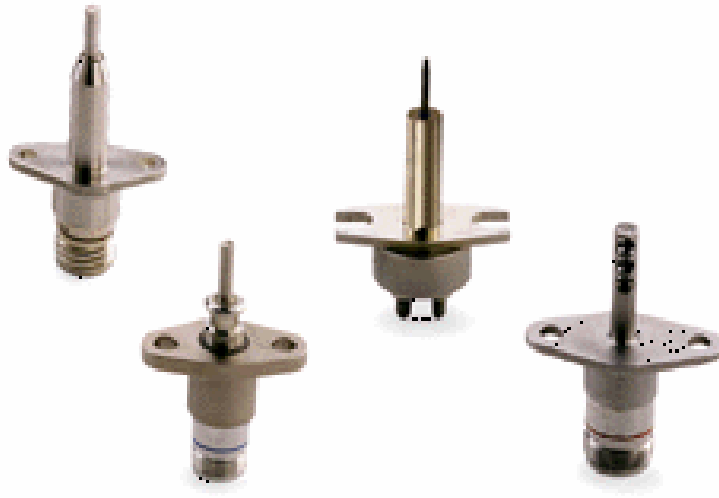
Figure 6.2: Resistant Temperature Devices (RTD).

6.3.2.1.3   *Engine Inlet Pressure and Temperature Probes*

GTE inlet pressure and total air temperature (TAT) are key engine control variables. Real-world flight conditions of accreting ice, foreign object debris and engine heat complicate accurate measurement of these parameters.

Available with either single or dual temperature elements and with an optional total pressure port, engine inlet pressure and total air temperature probes melt accumulated ice and prevent ice formation. Unique design characteristics ensure that engine or probe deicing heat does not affect sensor performance. These robust probes are qualified to withstand impact from damaging debris. Probe configurations protect sensing elements from abrading debris and provide years of uninterrupted service. Today, most aircraft power plants depend upon TAT or P2T2 probes to sense these critical control parameters.
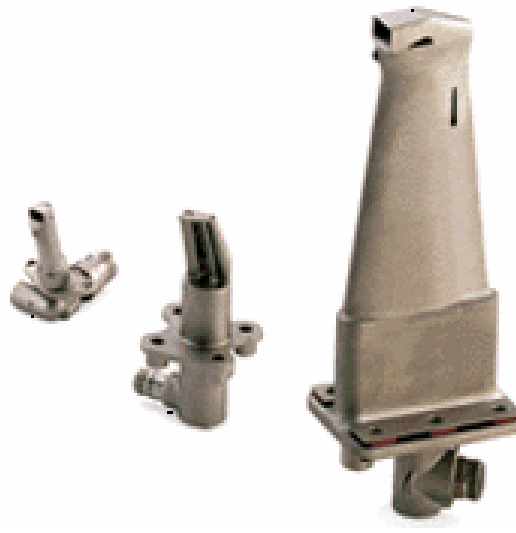
Figure 6.3: Engine Inlet Pressure and Temperature Probes [6.5].

6.3.2.1.4   K-Type Thermocouples versus RTDs for Temperature Measurement Comparison

Table 6.4: Comparison of Various Criteria of K-Type Thermocouples and Platinum RTDs

Criteria	Thermocouple	RTD
Accuracy @ 500 °C	2 °C	1.15°C
Stability	2 °C/year	<0.1°C/year
Temperature range	−270 to 1260 °C	−270 to 850°C
Sensitivity	40μV/°C	2mV/°C
Linearity	Moderate	Good
Type of measurement	Highest temperature	Average temperature

6.3.2.1.5   Radiation Pyrometer

The thermal efficiency of a turbine engine is determined by the increase in combustion gas temperatures. By using turbine temperature as a control parameter, engines can be adjusted closer to their thermal limit than with other means. Turbine blade pyrometers can detect a specific temperature at a specific point on a turbine blade. Fuel flow can then be adjusted precisely to maximize engine performance. Additionally, by monitoring the temperature of each turbine blade, pending blade failure can be predicted.

The Radiation Pyrometer is a non-intrusive sensor to directly measure the turbine blade temperature within a gas turbine engine. The Radiation Pyrometer consists of three main sections:

- The head assembly, mounted into the engine casing, receives the infrared (IR) radiation given off by the rotating turbine blades.

- The fiber optic bundle transmits the IR signal to the electronics assembly.

- The electronics assembly converts the IR signal into two electrical signals which are amplified, temperature compensated, and fed directly into the DECU or FADEC.

The unit is light-weight, highly accurate, and highly reliable:

- Accurate to ±4°C at 950°C;

- Measures blade temperature from 600°C to 1100°C; and

- Mass less than 1.2 Kg (3 lbs).

Figure 6.4: Radiation Pyrometer for EJ200 Engine for the Eurofighter Typhoon [6.6].

Figure 6.5: Turbine Blade Pyrometer with Fuel Cooling [6.5].

6.3.2.2   Pressure Sensing

6.3.2.2.1   Pressure Transducers and Switches

Pressure measurement applications include the monitoring and control of GTE gas path, oil, fuel, bleed air, engine torque, main gear box and auxiliary gear box lubrication oil.

The pressure transducers can use for sensing older technologies such as LVDT, potentiometers, variable reluctance, synchrous, etc.

For high accuracy pressure measurement, used mostly for gas path pressure measurement in FADEC, vibrating cylinder air pressure transducer is designed to measure absolute air pressure using the vibrating element principle, providing a frequency output from which pressure is computed. The pressure is applied to a thin-walled metal cylinder, which is set into motion at its natural frequency by electromagnetic drivers. As the air pressure inside the cylinder changes, the resonant frequency of the cylinder also changes. This frequency is

detected by electromagnetic pick up coils, which feed it back to the drive circuitry so as to maintain the resonant state. The 'new' resonant frequency can then be equated to the absolute pressure [6.2]. During manufacture the transducer is calibrated by measuring the resonant frequency (time period), and diode voltage (temperature) across a matrix of 77 data points (11 pressures, 7 temperatures), covering the full working pressure and temperature ranges. A 'curve fit' equation is then used to produce a pressure calculation algorithm. Such a pressure transducer has excellent accuracy parameters: Linearity <0.010% FSP, Repeatability <0.001% FSP, Pressure hysteresis <0.001% FSP, Temperature hysteresis <0.010% FSP, Stability(drift per year) max. 0.010% FSP; typical 0.005% FSP at the environmental conditions (to MIL-STD-810E) Standard –55°C to +125°C, Vibration 0.2g∑/Hz 5 – 2000Hz, Acoustic noise 140dB, Acceleration 20g.

Figure 6.6: Vibrating Cylinder Air Pressure Transducer of Weston Aerospace [6.2].

Most widely used current technology for pressure measurement is piezorezistive – Silicon-on-Silicon and Silicon-on-Sapphire technologies.

The **Silicon-on-Silicon** pressure sensors consist of a complex structure of three layers atomically bonded together. The first layer is of monocrystalline N-type silicon. This layer is micromachined into a mechanical force-summing diaphragm. The thickness of the diaphragm varies with the full-scale pressure range for which it is intended. The thickness is chosen so that this layer will see approximately 350 to 400 micro-inches per inch strain at that full-scale pressure. This is a very conservative level of strain for mono-crystalline silicon. The second layer, which is of silicon di-oxide, is grown right on top of the N-type silicon diaphragm. This layer provides dielectric isolation between the N-type silicon and the P-type silicon of the layer containing the Wheatstone bridge circuit, thus eliminating P-N junctions from the design of the device. The third layer is fusion bonded to the layer of silicon dioxide, at the intermolecular level, through a high-temperature process. This layer contains four strain gages of P-type silicon interconnected in a Wheatstone bridge circuit. The strain gages and their interconnections are one continuous integrated circuit of P-type silicon. The individual elements of this circuit are isolated from one another by a field mask of silicon dioxide, which is a continuation of the layer of silicon dioxide separating the layer of N-type silicon from the layer of P-type silicon.

The physical relationship between the locations of the strain gage elements of this third layer and the mechanical diaphragm of the first layer are such that, when pressure is applied, the resulting strain in the diaphragm causes two of the strain gages to go into tension (thereby increasing their resistance) and two of the strain gages to go into compression (thereby decreasing their resistance). The two tension legs are diametrically opposite each

other in the Wheastone bridge schematic. The same is true of the two compression legs. The result is that the applied stress causes an imbalance in the output of the bridge. The magnitude of this imbalance is directly proportional to the magnitude of the stress applied. This is the fundamental operating principle behind all "strain gage" pressure transducers [6.7].

Figure 6.7: Pressure Transducers of Druck [6.8].

The **Silicon-on-Sapphire** pressure sensor design incorporates silicon strain gauges configured as a fully active 4-arm bridge molecularly bonded to a sapphire diaphragm. Applied pressure induces strain resulting in a differential output voltage proportional to excitation and applied pressure. This construction takes advantage of material properties to provide a superior pressure measuring device. In the pressure sensor, a separate temperature sensing resistor, isolated from pressure effects, is located directly on the sapphire pressure measuring diaphragm. This integral temperature sensor allows ratiometric temperature compensation for highest accuracy. Pressure Sensors can measure absolute, differential or gauge pressure. Typical temperature range is from –55°C…+260°C [6.9].

In 2004, the aerospace turbine engine market was a, roughly, $45 million annual purchaser of high accuracy MEMS pressure sensors for engine control, stall protection, and health/performance monitoring. In this regard, Goodrich Sensor Systems is a significant participant in this unique market. Three important attributes of Microsystems Technology are very important to Aeronautic and Space applications: accuracy, reliability, and weight and usually require the performance accuracy and reliability over a very harsh operating vibration and temperature range [6.10].

6.3.2.2.2   *Piezoelectric Pressure Transducers*

Piezoelectric dynamic pressure sensors can be used for extreme temperature environments. The force created on the diaphragm is applied to the piezoelectric stack that produces an electric signal charges. The secondary effect of vibration is internally compensated. Thus the generated signal is purely proportional to the dynamic pressure applied to the diaphragm. The working temperatures of these transducers can be higher than 700°C. These types of transducers are used mainly for jet pipe resonance detection on various engines for military applications. State of the art devices have also been released with two channels in order that redundancy is "built in" and a better interface provided for BITE functions [6.6].

Figure 6.8: Dynamic Pressure Transducer for High Temperature Applications [6.6].

6.3.2.2.3   Differential Pressure Switches

Differential pressure switches basic design consists of an all stainless steel housing containing a piston/ management assembly, reed switch(es) and calibration spring. A high-pressure port located in the body behind an external "O" ring seal allows fluid to exert a force on the rear of the piston. The low-pressure port is located on the front of the body and allows fluid to exert a force on the front of the piston. The piston is maintained in its normal state by the calibration spring force. When the difference in pressure between the two ports increases to the point where it overcomes the spring force, the piston will start to move. The movement is monitored by the reed switch(es) sensing the magnetic field intensity with a resulting contact closure at a precise position. One or more reed switches are located in a cavity with proximity to the actuating magnet, but isolated from the system fluid. Such switches are adaptable to many differential pressure-sensing applications, are small in size and lightweight, and feature hermetically-sealed output switch contacts [6.3].

6.3.2.3   Speed and One-per-Revolution Phase Angle

Conventional speed sensors are based on the principle of electromagnetic induction and use a rotating gear tooth or phonic wheel to cut a magnetic path, inducing an alternating output voltage. The frequency of the output is proportional to the rotating speed. The conventional coil is simple but requires a large number of turns to generate a reasonable output voltage. In transformer speed probe the primary circuit operates at low voltage/high current, with a step up transformer on the output to give the desired output voltage [6.2]. Speed Sensors offer a mean time between failure in excess of 300,000 hours [6.5].

Figure 6.9: Speed Probes [6.2]-[6.8].

One-per-Revolution sensors are usually the stationary speed sensors that provide phase reference signal that gives information about the angular position of the engine Fan and Low Pressure Turbine required for cold fan trim balancing of GTE [6.11].

6.3.2.4   Torque

A conventional transformer speed probe can be converted into a torque sensor by using a torque shaft. As the torque changes through the shaft, the phase of the signal between the two sets of teeth changes. The transformer probe is superior in this type of application as it is less sensitive to variations in the gap between the sensor and the teeth on the shaft [6.2].
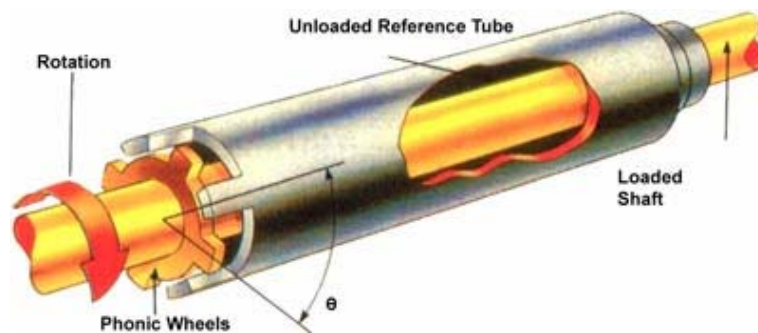
Figure 6.10: Torque Shaft with Two Phonic Wheels [6.2].

6.3.2.5   Position

Position is often measured with a Rotational or Linear Variable Differential Transformer (RVDT or LVDT).

6.3.2.5.1   Rotational Variable Differential Transformer (RVDT)

A RVDT is a transformer that provides an AC output voltage that is directly proportional to the angular displacement of its input shaft. The output signal is linear within a specified range of angular displacement. Both the primary and secondary windings are wound onto the stator of a RVDT.

6.3.2.5.2   Linear Variable Differential Transformer (LVDT)

A LVDT is a transformer that provides an AC output voltage that is directly proportional to the linear motion of its input shaft. The output signal is linear within a specified range of linear displacement. Both the primary and secondary windings are wound onto the bobbin of the LVDT. The RVDT and LVDT slug is passive and does not require brushes or a transformer to supply any current. The output of a RVDT or LVDT typically consists of two opposing voltages from the secondary.

6.3.2.5.3   Proximity Sensors

These sensors were developed as replacements for microswitch-based position switches and are used to detect for example to detect the door lock actuator position for thrust reversers. Proximity sensors utilize an air-gapped transformer to produce an electrical output as a ratio of excitation voltage. The proximity sensor produces an output dependent on axial or lateral position of a ferromagnetic target attached to the moving element of the

system or an output dependent on the position of a ferromagnetic core attached internally to the sensor plunger, which is in contact with the door lock actuator. By eliminating electrical switch contacts, reliability is greatly increased.

Figure 6.11: Proximity Sensors [6.6].

6.3.2.5.4   Magneto Optical Sensor (MOPS)
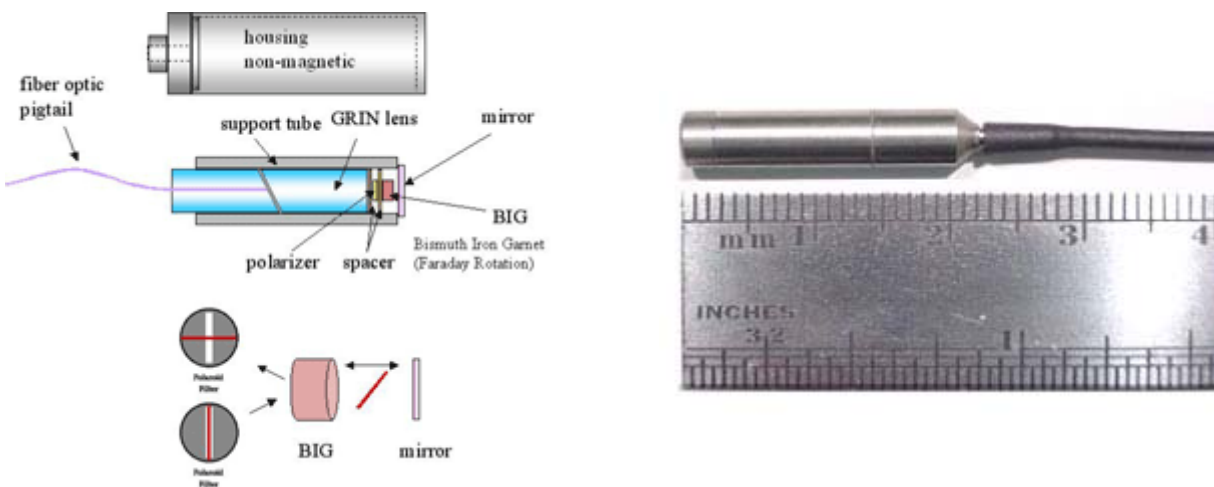
Figure 6.12: Magneto Optical Sensor – Principle of Operation and Size [6.4].

MOPS is a solid-state sensor with optical fiber transmission. A magnetic target is used in conjunction with the sensor. An interface card houses a bi-directional driver/detector and performs threshold and position decoding. Functionally, the sensor rotates plane polarized light as a function of the applied magnetic field. This causes a change in light output which is detected by the electronics [6.4]. The sensor has applications for proximity detection, displacement sensing, and angular rotation. This technology provides many advantages over products in use today for aviation applications, such as increased miniaturization, reliability, and standardization of sensor application.

6.3.2.5.5   Displacement

The working principle of the displacement transducer is the measurement of the variable inductance of a linear coil. The temperature compensation is built into the sensor and achieved by measuring the resistance of

the coil. The displacement measurement is made by measuring the reactance. The measurement system is lightweight and especially suitable for OEM avionics applications. This type of displacement transducer reduces the length of the space envelope by about 40% compared with LVDTs [6.6].

Figure 6.13: Displacement Transducer.

6.3.2.6   Fuel Flow

In the true mass fuel flowmeter fuel first enters the hydraulic driver, which provides the torque to rotate the shaft, drum and impeller. The fuel then passes through a stationary straightener and into the impeller. The mass of fuel flowing through the rotating impeller causes it to deflect proportionally against the spring. Impeller deflection relative to the drum is measured by pulses generated by magnets (attached to the drum and the impeller) rotating past two pickoff coils. The time between start and stop pulses, caused by the angular displacement of the impeller relative to the drum, is directly proportional to the mass flow rate of the fuel. True mass fuel flowmeter requires no external electrical power to operate. Typical temperature range is from –55°C…+200°C [6.9], MTBFs are currently exceeding 100,000 hours [6.3].

Figure 6.14: Mass Fuel Flow Meters [6.9].

6.3.2.7   Vibration

Majority of vibration transducers used for GTE are piezoelectric accelerometers, producing an electrical charge proportional to the acceleration parallel to the sensitive axis of the accelerometer. Piezoelectric accelerometers have no moving parts and are therefore extremely reliable.

A piezoelectric accelerometer is a mechanical assembly consisting of a number of piezoelectric forms (discs, squares or rectangles) and a seismic mass. A piezoelectric material gives an electric output when pressure is applied or conversely, changes its dimensions when an electrical signal is applied. An accelerometer uses this piezoelectric effect to convert mechanical energy into electrical energy. A piezoelectric accelerometer is fundamentally a mass spring system with a high resonant frequency, signals at frequencies up to one fifth of the accelerometer resonance frequency are unaffected by the resonant rise. Such a mass spring system can be used in the longitudinal axis if it is a compression mode sensor or in the transverse axis if it is a shear mode sensor. A newly patented push-pull system combines the advantages of both the shear and compression mode accelerometers. Typical accelerometer sensitivities range from 10 to 125 pC/g of acceleration, 50 pC/g has become industry standard for accelerometers monitoring vibration of GTE. Accelerometer have wide temperature range (up to 780°C). Customized, hermetically sealed construction of the accelerometer with or without integral cable, stainless steel, titanium or Inconel accelerometer housing combined with correct selection of accelerometer location and mounting, correct cable and connector selection, routing and clipping can provide vibration transducer with high reliability (MTBF > 100,000 hours), wide frequency range (up to 60 kHz), linearity (<1%). Such measurement requires special charge amplifier and signal conditioning [6.11].

Figure 6.15: Piezoelectric Accelerometers – Customized Designs.

6.3.2.8   Light-Off Detector

The LOD uses ultra-violet radiation detectors (UV tubes) that view the afterburner flame through a port in its liner. Critical attributes of this sensor are immunity to sunlight and rapid detection times despite exposure to afterburner temperature and pressures. Light-Off Detectors detect the presence of afterburner ignition on military aircraft.

6.3.2.9   Flame Contaminant Detector

Flame Contaminant Detector (FCD) has been used on various commercial gas turbine platforms to quantify the level of sodium entrained in fuel. The FCD consists of a spectrometer device, fiber optic cabling, and a lens assembly, which is mounted in an open combustor port. The radiant emission energy from a combustor is collected by the optical viewing port and transmitted to the array of sensors via the fiber optic cable. Each sensor assembly is configured to sense discrete spectral regions of flame radiation. Signals from sensors are then converted to digital format and presented to a signal processor. Algorithms verify the presence of combustion flame as well as the presence of selected contaminants such as sodium [6.12].

6.3.3   Summary of Current Technologies

The main type of sensors presently used in GTE for gas-path related measurements, including sensors for temperature, pressure and differential pressure, RPM, one-per-revolution, torque, vibration, position, and fuel flow measurement, are, if with integral electronics, limited to environment conditions within −65°C to +115°C. Sometimes the temperature limitations can be overcome with integrally attached electronics that is installed in the GTE location with acceptable temperature. These sensors were designed and packaged according to the specifications driven by the certification requirements to the aircraft and GTE. These current sensors are based on well-established sensing principles, including the Seebeck effect (temperature detection), piezoresistive, piezoelectric, and capacitive sensing, the photo-sensitive effect, inductivity, the inertial effect, the vibrating element principle, and the magnetic-optical effect.

By changing the packaging and/or design features of the system some of the current sensors can be modified to meet higher then present operating temperature ranges. Operation environments of 750°C or higher may be possible, which would meet requirements for sensors located towards the engine intake, compressor and in some cases low-pressure turbine. However, even if such sensors exist, they may not satisfy other essential conditions to operate within the propulsion system, including life, time between overhaul, reliability and small volume and mass. Also data processing of these transducers has to be carried out in a low temperature location. For sensor locations closer to the engine combustion chamber or afterburner, sensors withstanding even higher temperatures (up to 1700°C) are required. With an exception of thermocouples sensors for these temperature requirements do not exist.

There is also a need for sensors, which would enable future distributed control architecture. These sensors perform measurement, process data and take decisions, and provide feedback for actuation at the subsystem level, functions traditionally embedded in the FADEC. Because these sensors are located near the engine, they require operation in high temperature, which can be as high as 500°C. Presently these smart or intelligent sensors can be fabricated using silicon (Si) based technologies, which allows integration of sensing and signal processing and electronics at the chip level. However, since standard Si technology requires a junction temperature of less than 125°C, advanced technologies are required for high-temperature integrated sensors. Therefore it is currently not possible to transfer the processing from the FADEC to the sensing elements of the sensors with integral electronic installed in the locations with operating temperatures higher then approximately 100…115°C or cooling is required.

A number of sensors, which are of interest for more intelligent gas turbine engines, have not been implemented because the technology is not mature enough or do not yet exist, including tip clearance sensor, turbine emission species sensor, exhaust gas composition sensor, fuel quality sensor, burning patter factor sensor, other. Some of these sensors would make possible indirect measurements that are capable to yield information of the un-measurable quantities (for example thrust).

Implementation of available sensors is an additional major issue. Sensors should be small, light, low cost, and reliable. Also embedding of sensors within the structure of the engine is an issue that has been investigated by researchers, but has not been implemented in prototypes or even on military engines.

New sensing principles and technologies and their potential applications to new sensor technologies are discussed in the following section.

6.4 EMERGING TECHNOLOGIES

New sensing principles and technologies are needed to meet future sensor requirements, which cannot be fulfilled with current sensing principles and technologies, in particular the capability for operation in a high-temperature environment. Also, a number of sensors, which are of a significant interest for more intelligent gas turbine engines, do not yet exist or have been tested as research output for very limited conditions. Such sensors include but are not limited to tip clearance sensor, turbine emission species sensor, exhaust gas composition sensor, fuel quality sensor, or burning patter factor sensor. Some of these sensors would make possible indirect measurements that are capable to yield information of the un-measurable quantities as per today (for example thrust). The new technologies could be classified, according to their focus on new detection principles technologies or measurement in high temperature environments. The two foci are mainly coupled by the future needs in the propulsion system industry to achieve the adaptive distributed control more intelligent gas turbine engine.

New sensing principles and technologies as candidates for future sensors will be described first. Subsequently, examples for sensors, which explore these emerging technologies, will be also described. R&D needs / gaps and roadmaps for these future sensors will be summarized in Section 5. As introductory remarks for the discussions of emerging sensing technologies and sensors, the need for high-temperature operation capability and smart sensors will be re-emphasized, and the potential of microtechnology to address these needs will be briefly highlighted.

Most of the present sensors require very rugged packaging mainly due to the operation environment as well as reliability requirements. Specifications of the most of the present sensors with integrated electronics are limited to environment conditions within –65°C to +115°C. Few special sensors may work under very high temperature conditions (sometimes for only a limited time). Efforts of ongoing research are directed towards development of technologies to enable fabrication of sensors and miniaturized sensors with embedded electronics as well as integrated micro-sensors to operate at temperatures exceeding 200°C. Since the traditional Si based electronic circuits operate in environments with temperatures below 115°C, it is currently not possible to transfer the processing from the FADEC to the sensing element operating at high temperature towards a distributed control configuration. Great deal of effort has been directed towards the development of sensors with integrated processing electronics that will enable the above requirements at temperatures exceeding current rating of military or industrially rated electronic components.

Another general observation regarding delays of the implementing advanced active, intelligent, and distributed controls on the military aircraft propulsion systems is related to the slow progress of smart sensors. The smart sensors should have the capability to sense, process, take the appropriate corrective decision and provide the feedback signal and to send to the FADEC only the corrective action information for those system diagnostic purposes carried out at the central level. However, the intelligence of the sensor requires fusion of the transducer with the appropriate electronics and the resident software code. The challenges related to such an implementation are numerous. The fusion with the electronics requires the electronic circuit as close as possible to the sensing element, since the transmission error needs to be minimized. The power supply represents another issue, since power management to various intelligent sensing elements may come with multiple requirements. Moreover, the software codes should be conceived to enable fast and errorless communication with the FADEC. Smart sensors specs are made to satisfy the mass consumer, and any modification in the specs come with significant costs due to the reduced flexibility in the fabrication process. However, all the above issues could be addressed except one: the hardware electronic circuit that would be able to face the operating condition within the propulsion system. If sensors capable to operate up to 750°C may be commercially available, no commercially available electronic circuit could operate in temperatures exceeding 300°C (commonly,

115°C). This represents a significant gap that presently is addressed by researchers. Existing sensors overcome this gap by electronics integrally attached to sensor by an integral cable long enough to allow for installation of the electronics in the cooler location.

Micro-Electro Mechanical Systems (MEMS) technologies in general make a good candidate to address the need for high-temperature operation and smart sensor capabilities. MEMS is a concept of integrating electronics with sensing and signal processing at the chip level and provides advantages such as low mass, high reliability, low power consumption and low cost for large batches. Integration of Si-based electronics with microsensors using the same fabrication process has been demonstrated. The potential of MEMS is discussed in more details in the following, with specific emphasis on harsh environment MEMS and optical MEMS. In addition to MEMS as potential sensing technologies, other emerging sensing technologies, such as spectroscopy and laser diagnostics will be summarized.

The need for new technologies for high temperature sensing is also highlighted in Figure 6.16, illustrating the available sensing technologies for the specific temperature environments encountered in specific propulsion systems. Because of continuous progress on the sensors' performances higher temperatures are achievable now than shown in the figure. For example for piezoelectric technology, sensor designs are available that can work at up to 750°C using natural crystals, which is significantly higher then the 550°C shown in the figure for standard piezoelectric sensors.
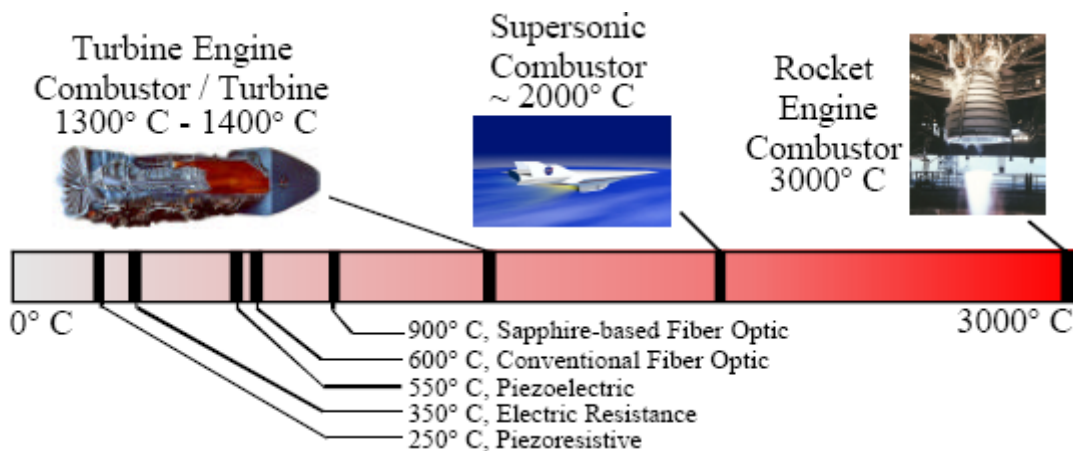
Figure 6.16: High Temperature Regimes for Sensors and Aerospace Applications [6.13].

6.4.1   Potential Sensing Principles and Technologies

6.4.1.1   MEMS Technology

MEMS provides potential benefits for future sensor technology, including miniaturization, increased reliability through redundancy, reduced costs, and the potential for development of smart sensors. Combined with other classical sensing principles, such as piezoresistive and piezoelectric and capacitive sensing and induction, MEMS is being explored as the basis for new types of sensors (for example for pressure). In addition, chip-scale gas analyzers are being developed using sensing technologies such as gas chromatography, mass spectroscopy, field ionization, Fourier Transform InfraRed (FTIR), surface acoustic waves, and resistance modulation by adsorption of gas molecules. Most of these principles are discussed in more details below.

MEMS also enables the development of smart sensors. Presently MEMS sensors are based on Si as the substrate material, which is also the material on which the electronic circuits will be deposited. This causes problems for high temperature operation, because Si junction implantations move deeper in the substrate at high temperatures. This makes Si based electronics to be bounded by 250°C operating temperature (lower is safer). In the following, potential MEMS technologies that will be associated with the operation at higher temperatures are discussed.

6.4.1.1.1   Silicon On Insulator (SOI)

Silicon on Insulator (SOI) technologies are based on standard CMOS (Complementary Metal Oxide Semiconductor), in which the diffusion is limited by an insulating layer and junction impurities will not move deeper in the substrate at temperatures above 250°C. Since the substrate is only few tens/hundreds of nanometers thick, in-depth diffusion of the active components is prevented and operation up to 300°C is possible. However, at temperatures exceeding 300°C, the migration of the carriers commences to occur in lateral direction, which will yield to the out of service transistor/diode junctions. Yet, some gain of about 50°C in the operating temperature has enabled applications that were unlikely to be realized in basic Si technologies [6.14]. Some industries have already launched applications for such technologies such as Kulite for the pressure sensing in high temperature applications (up to 300°C).

6.4.1.1.2   SiC

Silicon Carbide (SiC) technologies are based on similar CMOS technologies used for Si. However SiC, a semiconductor, could withstand temperatures as high as 500°C. At the present time there is no planar technology to enable electronic circuits exclusively be made in SiC that could support the integrated sensor. However, there are significant efforts in the development of commercially level planar circuit technologies for SiC, and the forecast predicts such technologies at the prototype level by 2010 – 2015.

Since the capability is limited by the material properties, the research has encompassed the material science. SiC has gained interest on mid 90's due to the semi conducting properties as well as the standing capability to the impurity diffusion into the material at higher temperatures than the temperatures that SI is standing. Such, the electronics in SiC is expected to stand temperatures as high as 600°C and, under long time exposure, up to 450°C. The present technologies could provide individual power switches and diodes in SiC, while individual transistors have been produced in the NASA labs. It is foreseen that in 5 to 7 years, the surface fabrication technology for SiC will mature to the extent that complex circuits and compensators could be realized and made reliable enough to operate in a propulsion system.

SiC can provide a solution to few specific issues encountered in the propulsion systems, but as per today knowledge, the technology is limited to 600°C [6.15]-[6.19].

6.4.1.1.3   SiCN

Silicon Carbide Nitride (SiCN) technologies are based on very different grounds as the SOI or SiC technologies, since SiCN is not a semiconductor, but a high temperature withstanding ceramic material. At the present time, the technology is little developed, but it has a great potential in being used to develop sensors to operate in temperatures higher than 800°C.

The temperature constraint is quite stringent, since sensors operating up to 1700°C may be required in the concept of the distributed controlled propulsion system. The intrinsic properties of SiCN make possible that

SiCN would be capable to stand 1700°C without thermal softening, so that the material could be used for transducing assuming that a suitable sensing principle could be associated with the material. A lot of research has been carried out in developing fabrication processes for the hard and brittle SiCN ceramic. A pyrolysis-temperature cycle process enables fabrication of SiCN from Si thermosets polymers. The process also enables accurate shaping of the polymer and, in consequence, of the ceramic component.

A great deal of effort has been directed towards the optimization of the temperature-cycle that would yield stress free controlled thickness layers. In the effort to create conductive films in SiCN, controlled doping with various III-V group elements and also using various metallic materials (Cu, Al, Fe). The preliminary investigations have indicated that SiCN doped with Fe exhibits electro-magnetic properties that may make it suitable for a special type of electronics – spintronics [6.20]. This technology is discussed in detail below.

SiCN technologies are still at a very early leveling the progress and very limited number of applications has been achieved by SiCN or SiCN composite. A horizon of 10 – 15 years is foreseen under the present conditions of interest that SiCN has stirred. Apart form sensing, the conditioning circuits would be required to achieve the level of intelligence of a sensor that Si technologies could yield today.

6.4.1.1.4   *SiCN and Fe Composite Material*
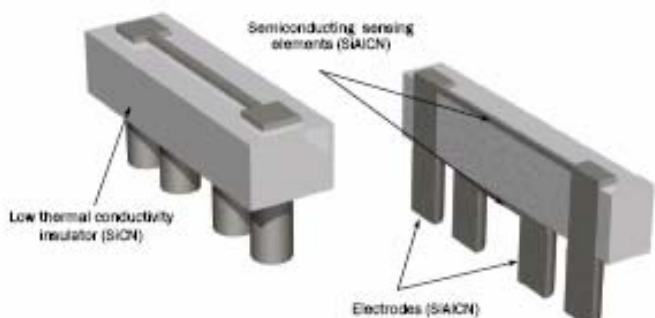
Silicon Carbide Nitride doped with Fe ions yield special supra-paramagnetic properties to the ceramic. The magnetic properties are maintained up to 1340°C. As the material could be grown in crystals of small size, the magnetic properties could be controlled. Such material could be used for measurement of temperature. Preliminary studies indicate that the strain modifies the crystal size and the magnetic properties. This is an indication that such composite could also be used for pressure measurement at high temperature.

The example illustrated in Figure 6.17 is a research perspective from the University of Michigan. Recent works have indicated that under a certain pyrolysis process, SiCN could grow in single crystals. SiCN doped with Al produced a piezoresistive element capable to detect temperature and temperature gradient with high accuracy in very harsh environment conditions.

Figure 6.17: Potential SiCN Applications.

The magnetoresistance properties of the SiCN and Fe composite material at high temperatures (up to 1410°C) along with the possibility of electric resistance modification make these materials a good candidate for spintronic applications as discussed below.

6.4.1.1.5   Spintronics

Spintronics devices are playing an increasingly significant role in high density data storage, microelectronics, sensors, quantum computing and bio-medical applications, etc. While conventional electronic devices are based on the transport of electrical charge carriers – electrons/holes – in a semiconductor such as silicon, spintronic devices manipulate the electron spin, as well as the charge, for the operation of information processing circuits, based on the fundamental fact that electrons have spin as well as charge. All spintronic devices act according to the simple scheme:

1) Information is "written" into spins as a particular spin orientation (up or down);

2) The spins, being attached to mobile electrons, carry the information along a conductor; and

3) The information is read at a terminal.

Spin orientation of conduction electrons survives for a relatively long time (nanoseconds, compared to tens of femtoseconds during which electron momentum decays), which makes spintronic devices particularly attractive for memory storage and magnetic sensors applications as well as other classical sensing applications (piezoresistive, piezoelectric, tunneling, etc.) and, potentially for quantum computing where electron spin would represent one bit, called qubit of information. These spintronic devices, combining the advantages of magnetic materials and semiconductors, are expected to be non-volatile, fast and capable of simultaneous data storage and processing, while at the same time could be smaller, require lower power consumption, be more versatile and more robust than those currently making up silicon chips and circuit elements.

6.4.1.2   Optical MEMS Technologies

Optical MEMS have gained significant interest lately among various microsystems dedicated research teams [6.21]. The main challenges associated with the implementation of optical systems within a microelectronic chip are overcome by the great benefits that optical imaging could bring to the propulsion systems. Imaging enables digital analysis of arrays of information such as temperature gradient distribution or gas species composition through spectral analysis. The acquired information directly could be processed by the CPU. The main disadvantage of the array imaging is associated with the limited type and operation and speed they can perform. Enhanced performance through improved high speed and high repeatability associated to extended wavelength sensitivity and capability to serve high temperature environment are among the main advantage of the optical MEMS arrays.

Optical sensors may be realized in small size although not necessary using a batch technology and they could be used for various detections including the ones associated with the enhanced performance of the propulsion systems. Optical fibers and gratings may be used to measure temperature distribution in a compressor. The temperature limits the functionality of the gratings in an optical fiber, even if made form a highly refractory material.

There are challenges that the optical systems including optical MEMS must face apart from the high temperature challenge: contamination, diffraction change with temperature, the proximity of the data processing circuit to the detection system. The associated challenges are specific to the sensing technology in general and such challenges are foreseen that could be overcome through the development of materials which have properties that are not highly affected by their extended exposure to high temperature.

The Micro-Opto Electro Mechanical Systems (MOEMS) face the same challenges as MEMS face in packaging, integration and extended service over harsh operating conditions. The solutions to the problems are somehow similar to the ones encountered in MEMS: the new technologies should commence with new materials.

6.4.1.3   Signal Transmission

The classic signal transmission technology continues to be used of the same fashion through reliable connectors and wires. The wireless data transmission technologies, although not yet matured, pose significant challenges when required to perform within 99.99999% reliability in a GTE environment (RF, blue tooth, WiFi). They also require for long term operation of the engine some energy harvesting or scavenging technologies to provide

power to the sensor when not connected by wire to the power supply. However, such technologies are not exhausted as new and novel research is carried out in the telecommunication technologies. The high temperature electronics would facilitate the errorless signal transmission for sensors that have to operate under high temperature conditions.

6.4.1.4   MEMS Packaging

Along with sensor development, packaging recipes and strategies for harsh environment require significantly more attention. From the to-date experience, packaging of MEMS devices is considered the same as packaging of the Integrated Circuits. Very little attention has also been paid to the sensors embedding within the structure of the engine mainly due to the strict regulatory requirements of the airspace products. The packaging requires to satisfy conflicting requirements that come form the structural integrity requirement, reduced mass and non-interference with the flow path, to name only few of such requirements [6.22] [6.23]. The challenges associated with the reduced integrity of the structure in a GTE when microstructures are embedded are perceived as a major factor of progress in the embedding technologies. This approach requires extremely high reliability for the sensors, condition which is not fully satisfied at the present time or foreseen as achievable in the near future. Although the embedding is seen as a very much customized operation, the benefits of sensing are fulfilled when such embedding prevents addition of bulky packages that usually interfere with the flow path. Research projects have addressed the embedding issue and such example is shown below. Defense Evaluation and Research Agency (DERA – UK) in collaboration with Ohio State University have embedded thermal sensors in the turbine blade to optimize the heat transfer distribution through the blade. Based on the same principle, pressure of miniaturization for embedding ability, pressure sensors is definitely following into being integrated within the engine structure. It is expected that the first attempts will be made in the fan/intake region.
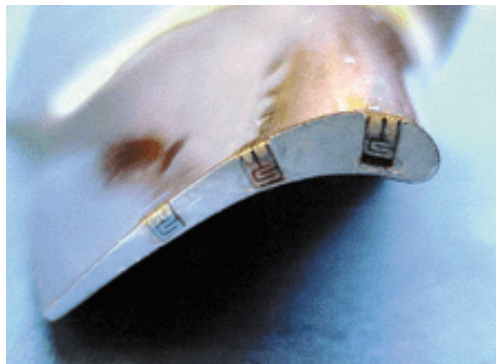
Figure 6.18: Embedded Thermal Sensor [DERA].

6.4.1.5   Spectroscopy and Laser Diagnostics

6.4.1.5.1   *Spectroscopy*

Spectroscopy, which identifies substances through the spectrum emitted from them, has been utilized in combination with MEMS to develop chip-sized gas analyzers. These sensors are based, for example, on Fourier Transform InfraRed (FTIR) spectroscopy (spectra are collected based on measurements of the **temporal coherence** of a **radiative** source), laser induced breakdown spectroscopy (utilizes a highly energetic **laser** pulse as the excitation source of elements to be detected), mass spectroscopy (analytical technique that measures the

mass-to-charge ratio of **ions** and finds the composition of a physical sample by generating a **mass spectrum** representing the masses of sample components), and Raman spectroscopy (which relies on scattering of laser light in the system).

6.4.1.5.2   *Tunable Diode Lasers (TDL)*

Wavelength tunable TDL technology, based on telecommunication-type devices operating in the visible and near-IR portion of the spectrum, is being explored for real-time measurements of important propulsion parameters [6.24] [6.25]. This technique for line-of-sight integrated measurements is using well-understood absorption spectroscopy. The TDL lasers are quite economical and extremely robust, and can generally be coupled to optical fibers to allow transmission of light to and from measurement locations. The relatively low cost and robustness of TDL sensors, combined with fast response and relatively simplicity of operation and data interpretation, have led to rapid progress in the application of these sensors to practical combustors and have demonstrated the unique potential for control applications. Figure 6.19 demonstrates a strategy for GTE application, which allows sensing of multiple flow field parameters, including temperature, species concentration, pressure and velocity [6.26].
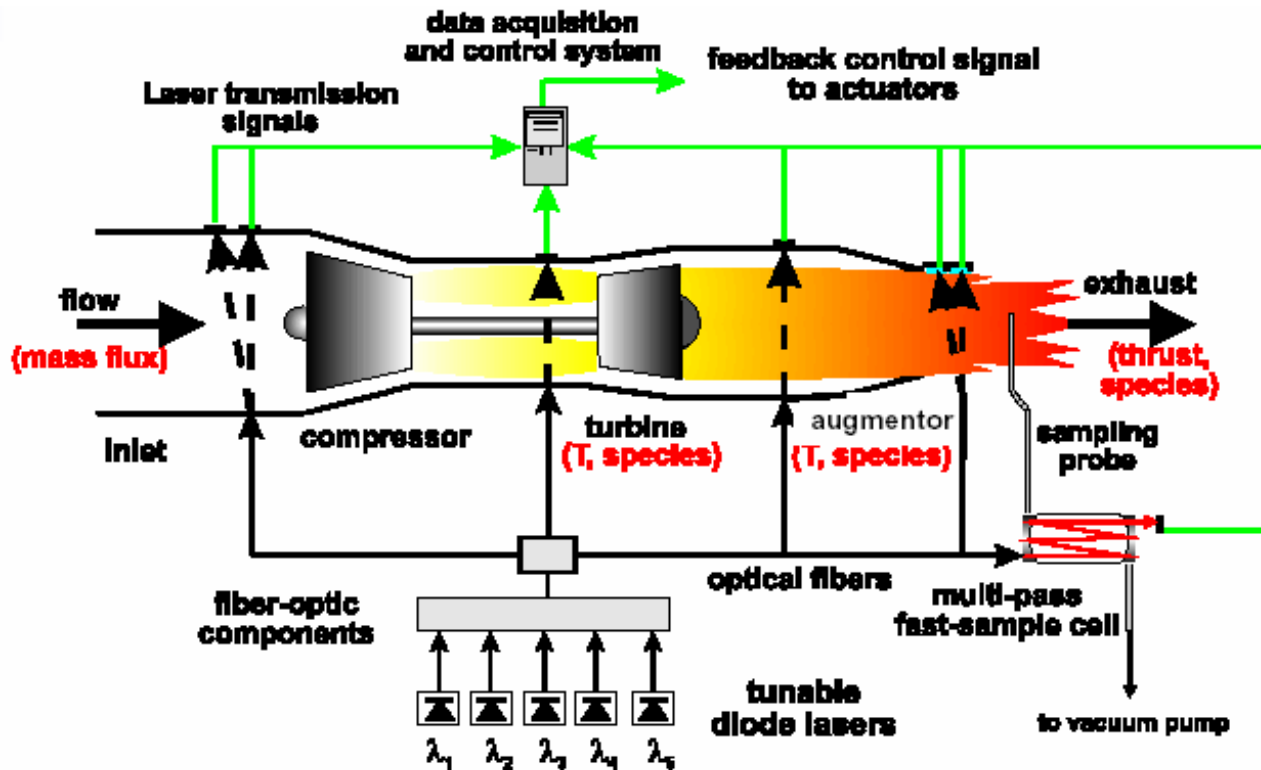
Figure 6.19: TDL Sensors for Multiple Flow Measurements [6.26].

6.4.1.6   Other Advanced Sensing Principles

Other gas sensing principles, which are being explored for advanced sensors and discussed in the following include:

1) Modulation of the resistance of metal-oxide element by adsorption of gas molecules, in particular with metal oxide nanostructures (gas sensor arrays);

2) Surface Acoustic Waves (SAW) (gas sensors);

3) Gas chromatography (gas sensor);

4) Ion detection (flame blow-out);

5) Acoustics detection (flame blow-out, health monitoring);

6) Electrostatic sensors (gas path debris detection);

7) Microwave, eddy current, capacitance transducers for various applications, including tip clearance measurements; and

8) Doppler Velocity Interferometers (vibration).

Several gas sensor approaches are described in the following in more detail. In gas sensors using the absorbing properties of metallic oxides at high temperatures, specific gases are selectively absorbed by various porous layers of oxides, which would modify some of their properties including electrical resistance and capacitance. The Surface Acoustic Wave sensors make use of a so called delay line that is located between an emitter and a receptor all positioned on a piezoelectric surface. The delay line is made from a sensitive material to the detected gas that would modify the acoustic wave produced by the emitter. The amount of distortion is detected by the receptor, and it is related to the amount of the absorbed gas. In gas chromatography a moving gas called mobile phase carries the samples over a stationary phase. However, only 10 to 20% of the known compounds could be analyzed through gas chromatography. Only phases that could be vaporized below 450ºC could be analyzed by gas chromatography. The ion detection is based on the separation of bunches of ions according to their individual mass to charge and recording of the amount of such sorted groups of ions through various methods such as energy level detection. The acoustic detection is based on the principle that a corrupted structure would yield sound of different spectral components than that of the same fully integer structure.

A class of capacitive sensors could be used for debris detection. When a gas carried ferromagnetic particles, the electric/electromagnetic field that they cross will be distorted by the metallic field modifiers. The distortion could be calibrated and used for measurement. Microwave sensors are based on a similar principle. A high frequency electromagnetic wave is generated by a source and the echo is collected back by the reader that would associate the reading with a specific perturbation, usually created by a ferromagnetic material. Similar principle is used by the ultrasonic or by eddy currents, while use ultrasonic or electromagnetic fields. Doppler velocimetry is based on the frequency and phase shift collected from an out of plane moving object of a reflected coherent light source compared with the incident one. Although these are valid measurement principles which are dominantly used in other applications than the propulsion systems, they might, in case of a stringent need, be adjusted to fit propulsion systems applications. The major problem that is foreseen as to be encountered is the harsh temperature conditions that sensors at specific location in the GTE must face.

6.4.2   Emerging Sensors

6.4.2.1   Temperature

The gas-path temperature is measured throughout the propulsion system mostly by immersion thermocouples; in some GTE optical pyrometers are used to measure turbine blade surface temperature. There are also few applications to measure burner patter factor or the surface temperature of the turbine stator for extension of the

burner and turbine life. Although these applications are addressed at this time through modeling and simulations, the lack of accuracy of the methods could yield erroneous results.

There are various attempts to measure the burner patter factor through spectrometry [6.27] or through IR pyroelectric detection [6.28] [6.29]. Although the proposed methods yield good results, they are questionable for the propulsion system for military applications, where the weight is a primary concern. Moreover, problems such as contamination of the vision window for pyroelectric detection may be of a serious concern for achieving high accuracy. Regular scheduled maintenance actions would be required, which make this technology currently not suitable for commercial GTE.

Other technologies are at the fundamental research level [6.30] [6.31], but they have shown a high potential in overcoming many other issues associated with sensing under high temperature conditions. Ceramic materials from polymer precursor, such as SiCN, have proven to be appropriate to perform accurate detection tasks under extremely high temperature environment. Such sensors may be used for temperature applications as well as for detection of pressure or gas composition.

The TDL technique for measurements of temperature (and other sensed variables as discussed below) has been demonstrated on full-scale gas-turbine combustor sector test stands [6.32] [6.33]. However, challenges include "optical engineering" (dealing with heat transfer effects on fibers and windows and developing robust hardware designs for these components and also for lasers, electronics and data processing) and "optical science" (optimizing the selection of wavelengths and sensing strategy).

6.4.2.2   Pressure

Pressure sensors must achieve specific performances under the environment conditions associated with their location. Although technologies, that enable pressure measurement under environment temperature to about 750°C, are commercially available, such sensors/transducers are used mostly on the test stand, because they cannot measure also static pressure. Miniaturization is of great interest for propulsion system applications, mainly because of the potential of *embedding* such sensors within the structure.

Pressure sensors for the ***active inlet control*** (3 bar operation pressure, $\pm 0.1\%$ accuracy, $-60°C$ to $+65°C$ temperature environment) provide challenges, such as harsh environment, induced permanent and random drift, complex circuit, and complex packaging. Such sensors are not available at this time, however, they could be retrofitted from other aerospace applications. MEMS technologies seem quite appropriate for this type of applications given the capability and potential for miniaturization and embedding and high reliability. The harsh environment (ice, rain, sand, dust) may be mitigated through appropriate packaging of the sensor arrays. Multiple general purpose technologies are available at this time, but all will require some time for maturation related to the integration of the sensing array within the system. A great deal of effort is associated with packaging of such sensors, and embedding is foreseen the most appropriate option at this time, although reliability of miniature sensors might play the limiting factor in such an undertaken.

Inlet ***distortion detection*** to manage engine stability limit require static pressure arrays with $\pm 0.25\%$ resolution, 500Hz bandwidth, and -50 to $+65°C$ operating temperature. Such sensors are available in MEMS or other technologies.

A method of and apparatus for detecting air distortion at the inlet of a turbine engine is proposed in [6.34]. This method adjusts fuel flow to anticipate and prevent compressor stall. A plurality of pressure taps are arranged in a spaced relation around the periphery of the engine inlet. A distortion detector senses the differential pressure between the instantaneous pressure at each pressure tap and the ambient pressure of a reference pressure

chamber, which communicates with the plurality of pressure taps. At a predetermined pressure differential the distortion detector activates a solenoid-operated fuel bypass valve, which reduces fuel flow to the fuel nozzles of the gas turbine engine.

Pressure probes equipped with fast-response transducers have been successfully used in axial-flow compressors and turbines, but have been rarely used in centrifugal compressors. The associated challenges are: complex and heavy wiring, complex data acquisition, and dedicated circuits for temperature correction. However, this technology can be immediately implemented under the provision that the integration is enabled by the propulsion system manufacturers.

Sensors for early *detection of stall* (35 kPa dynamic pressure, + 0.2% resolution, 5 – 40 kHz bandwidth) are also available in MEMS technologies. The current practice in gas turbine engine design is to base fan and compressor stall margin requirements on a worst case scenario with an additional margin for engine to engine variability. These factors include external destabilizing factors such as inlet distortion, as well as internal factors such as large tip clearances. This approach results in larger than necessary design stall margin requirement with a corresponding reduction in performance and/or increase in weight. However, the harsh thermal environment has limited the use of pressure transducers to ranges below 250°C, thereby effectively precluding measurement at the final stage exit where temperatures are typically in excess of 450°C depending on the type of compressor. Piezoelectric dynamic pressure sensors are available for monitoring pressure pulsation, although they cannot measure static pressure they can be used for detection of stall and surge of engine compressor, including the high pressure compressor discharge stage. Certain burden is that the aerospace GTE, compared with industrial aeroderivative GTE, does not allow yet for controlling fuel delivery to each individual fuel nozzle. Si and SiC based pressure transducers experience operating conditions under limited temperature. They experience limited life and, commercially available sensors are not directly implantable on a flying propulsion system. Hence, silicon carbide (SiC) or silicon carbon nitride (SiCN) based MEMS technologies are further considered as possible solution for the design of high temperature pressure transducers [6.35]. Both SiC and SiCN technologies come with a potential of being able to provide embedded low-cost microelectronics that operates at high temperatures [6.36]. The availability of a sensor system that could detect the onset of stall could allow these margins to be safely decreased [6.37].

Sensors for *active surge control* commonly operate in temperatures ranging from –60°C to +500°C and up to 700°C, while the pressure environment ranges from 15 to 1800 kPa. The measurement requirements are for 35 kPa dynamic pressure, 1 Hz bandwidth, and +0.5% resolution. Active surge control is used to reduce the design surge margin of gas turbine compressors while maintaining sufficient engine dynamic and tolerance to inlet distortions, thereby obtaining more efficient propulsion systems. This can be achieved either by reducing the stage count or increasing the pressure ratio with the same number of stages. As this requires a system that assures the aerodynamic stability of the compressor in all operating conditions, different schemes of active control systems have been proposed and tested for high speed machines. These types of systems rely on the early detection of incipient instabilities. Since engine accelerations and inlet distortions are the most significant causes for a reduction of operating surge margin under real flight conditions, the influence of these effects on the instability inception has to be investigated [6.38]. Piezoelectric pressure pulsation sensors to operate below and even above 500°C up to 750°C are available, however they cannot measure static pressure.

Sensors for *flow separation detection* require two static pressure taps at distributed locations across the flow control vane. The requirements are ±0.3 atm dynamic pressure range, ~±0.5% accuracy, ~ 1 Hz bandwidth, ~80°C, and ~2.5 atm operating environment. The static pressure sensors can be also case mounted. One method for flow control sensing to control surge/stall proposes a plurality of skewed slots of a particular shape located within a compressor casing adjacent to at least one stage of the compressor blade tips, where the

slots have an axial length greater than that of the adjacent blade tips. The slots are provided such that upon occurrence of compressor surge or stall, the stagnating air occurring about the blade row may be directed by the slots downstream of the compressor blade row back into the main stream of fluid passing through the compressor. By such an arrangement, the slots provide a compressor in which the air flow and pressure ratio may be increased before reaching compressor stall or surge [6.39]. The associated challenges are related to the complex and heavy wiring while earlier prediction requires higher environment temperature. Synthetic jets may be part of the active flow control scheme.

Detection of **thermo acoustic instabilities** requires pressure sensors with 10kPa dynamic pressure, ±5% resolution, and 1 kHz bandwidth at an operation temperature of up to 1700°C. Most combustion-driven devices experience combustion instabilities. During aircraft turbine engine operation, the augmentor (afterburner) operation is often associated with combustion instabilities that can be potentially detrimental to the turbine engine if the resonant amplitude levels are excessive. Oscillation in the frequency range of 50 – 100 Hz is commonly called "rumble," whereas higher frequency oscillation, up to 600 Hz, known as "screech."

The challenges are related to the extremely harsh environment. Practically it is not possible to instrument a burner in the classical approach for on-flight control. Optical temperature measurements as alternative to pressure sensors and new materials for pressure sensors are being explored as described in the following.

A novel remote sensor system has been investigated to determine incipient combustion instability and ultimately provide feedback for combustion control. The sensor is based on high speed measurements of the radiant emission from the hot exhaust stream. In this approach, select infrared wavelengths of light are used to capture temporal variations in the radiance [6.40]. Also TDL temperature sensors could substitute for pressure sensors.

Lately a lot of interest has been made public by many research groups in relation with new materials (SiC, SiCN) and concepts for sensing that could lead to the development of sensors that operate at very high temperatures. Very little research has been done in packaging which includes, for this specific application, wiring. Sensors to operate under the conditions of the maximum temperature encountered in GTEs cannot be addressed as per today technology to achieve portable and reliable sensors. Such sensors are not presently available for applications that require reliability and steady performance in time. This gap could be addressed by the development of SiCN material and technologies as one of the very few option for sensing although aspects such as wiring and packaging are still unsolved. Sustained research in SiCN may yield to the enhancement of the material capability to operate as a semiconductor (spintronics), that would enable development of intelligent sensors that could operate in very harsh environments (in excess of 1000°C) [6.41]. Meanwhile, there are several efforts in remote sensing principles, which in conjunction with the potential progress that will be made in new materials development, could yield to solutions to the needs of the distributed control design concepts. The progress on the two research directions will depend on the amount of funding that will be allocated to the two topics.

6.4.2.3   Vibration and Acceleration

Vibration and vibration amplitude are mainly used to detect potential mechanical failure in the propulsion system. The distributed control strategies focus on the detection of the mechanical failure in the fan and in the turbine. Both situations require accelerometers that could operate within the environmental conditions imposed by the measurement section. However, for the turbine, there are means of indirect measurement that could be performed and which could yield significant information from locations that are in the vicinity of the turbine. It is important to mention that such a measurement is highly affected by noise.

Vibration sensors – either standard inertial sensors or optical sensing (Doppler Velocity Interferometers – non-contact) – could operate within the specifications required by the operation conditions of the GTE with frequencies up to 40 KHz, accelerations up to 1000g, selectivity to 3%, temperature range from –65°C to +750°C. Inertial sensors – piezoelectric accelerometers and non-contact Doppler Velocity Interferometers are ready available. The critical aspect is related to the fact that non-contact Doppler Velocity Interferometers would measure a relative acceleration of the targeted location vs. the position at which it has been assembled. Application of this sensing method is extremely difficult in an aerospace engine because an accurate relationship of the phase between the two sections is critical for yielding accurate measurements. Therefore piezoelectric inertial sensors – accelerometers are used on majority of GTE. Such sensors are appropriate for fan health monitoring, but they require significant improvement when used for the turbine. The major drawback in current condition monitoring methods through vibration measurement is the integration of sensing, signal processing and the model. This could yield unacceptable threshold values. The high temperature measurement still needs the physical detection system along with the signal processing that could operate under high temperature conditions. The two above mentioned technologies (SiC and SiCN) may yield accelerometers to operate within the required range for turbine health monitoring. Fabrication of inertial sensors poses very little challenges as long as the main technology is available for commercial use.

6.4.2.4 Emission Species

Combustion emissions measurement of CO_x and NO_x at the HP stator vanes, with 5% resolution, 5 Hz bandwidth and 700 to 1700°C environment are of interest for emission control. Such sensors are not available. Sensors that could detect CO_x and NO_x are available to operate under normal temperature conditions. However, in order to perform such a measurement, the gas that contains the species needs to be energized, mainly by heating. The measurement technologies require high temperature for the detection species, while the hardware is either locally heated or kept at the environment temperature. For an example, two of the components of the complex NO_x such as NO and NO_2 react at high temperature and release specific wavelength radiation that can be detected by tuned detectors. Among the technologies that enable detection of CO_x and NO_x are: laser-induced breakdown spectroscopy, TDL, metal-oxide based sensors (electronic noses), X-ray or Infra Red spectroscopy. All the above technologies may be able to yield reliable sensors for GTE emission species detection. The implementation of such type of sensors for GTE applications might requires more effort than the development of other type of sensors, since all the above technologies are laboratory tools only, while the portable equipment is less accurate.

Still, such systems are at the proof of concept research level and significant technology improvement is necessary to have such detection systems fully implementable in flight. Gas specimen detection is not limited to NO_x or CO_x but it can extend to Fe_xO_y or Cr_xO_y, which, if accurately detected, could provide very good information about the condition of the burner and/or the turbine. Laser-induced Breakdown Spectroscopy is one potential option and miniaturization of the spectroscopic hardware is an ongoing research topic. Although not conceived to be implemented on a flying engine, the technology has proved reliable for the ground applications. [6.42]. The method provides accurate measurement of elements such as Al, Ba, Be, Ca, Cr, Cd, Cs, Fe, Mg, Mn, Na, Ni, Pb, Se and V. As all the other sensing systems that are required to operate in high temperature environment, SiC and SiCN may be potential solutions for the application. The topic is of great interest in developing the ''green engine'' in the accomplishment of low emission engines.

A complete active control system – sensing, actuation, and control algorithm – has been developed that can prevent lean blowout (LBO) in gas-turbine-type combustors and was demonstrated in a premixed, atmospheric-pressure model combustor. The system is designed to minimize NO_x by ensuring safe operation at lean equivalence ratios. The system was effective in operating the combustor at a reduced NO_x index by

reducing the allowable equivalence ratio in the reaction region of the combustor [6.43]. Such systems have been implemented on ground (power generating) turbines but the implementation of such systems in flight poses challenges that are related to the integration, mass and reliability.
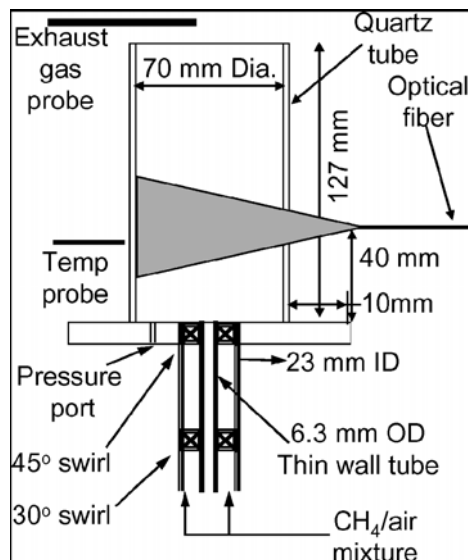
Figure 6.20: Prevention of LBO to Allow Operation at Reduced NO$_x$ Combustor Schematic Showing the Viewing Area for the Optical Fiber Used [6.43].

6.4.2.5   Tip Clearance and Tip Timing

Blade tip clearance varies over the operating points of the engine. The principle mechanism behind these clearance variations comes from the displacement or distortion of both static and rotating components of the engine due to a number of loads on these components [6.44]. Loads can be separated into 2 categories: engine and flight. Engine loads produce both axisymmetric and asymmetric clearance changes. Flight loads produce asymmetric clearance changes. In this regard, blade tip or outer air seals line the inside of the stationary case forming a shroud around the rotating blades, limiting the gas that spills over the tips The tip clearance mechanisms are imposing on the tip clearance sensors to operate within the environment conditions of the section of the compressor or turbine. In the compressor, the environment conditions are: 15 – 1800 kPa, –60°C to 700°C. For the tip clearance of the turbine, the environment conditions are much harsher: 300 – 4000 kPa and 700°C to 1700°C. For such type of applications there is no commercially available sensor, but there are intense investigations on the possibility to measure on the ground the clearance and relate that with the turbine performance [6.45]. A number of patents have been filed with this subject [6.46] [6.47]. Although the patents claim control capabilities of their systems, the sensing is not addressed in detail. Many types of sensors have been implemented in attempts to measure turbine blades during operation – electromechanical, capacitive, eddy current, optical, pneumatic and microwave probes [6.48].

6.4.2.5.1   Electromechanical

These devices couple mechanical action and electrical sensing to make measurements. The first electromechanical sensors used an electrode to detect clearance between the stationary stator vanes and the rotating drum. The drum is first coated with an electrically conductive paint and grounded, and the electrode is lowered mechanically by means of a precision stepper motor until an electrical charge arcs across the gap to

the rotating drum. The distance between the electrode and blade tip is calculated based on the voltage of the charge; a clearance measurement is calculated by adding the distance that the electrode is lowered into the turbine. A microcontroller detects the flow of a charge, and moves the electrode in and out in response. The response speed of the system is limited to less than 10 samples per second, and the resolution of the system is limited by the resolution of the stepper motor motions and the pitch of the lead screw driving the electrode into the turbine. A second generation model of electromechanical blade tip measurement system demonstrated its durability up to 1500°C under the normal vibrating conditions of a running engine. This version measures passing blades rather than a rotating drum, and operates by driving an electrode down from the casing toward the blades with a stepper motor until it is close enough to the passing blade tips (within 3 to 5 μm – about 0.0002 in.) for an electrical charge to arc. They report an accuracy of 25 μm (0.0010 in.) over a 6 mm (0.2 in.) range; however, the sensor is only used to measure the clearance between the casing and the longest blade, since it cannot extend farther towards the other blades without being hit by the longest blade. A third generation model of the Stepper Motor Driven Probe uses the same design concept to measure the longest blade with a mechanical probe that sparks when it comes close enough to the blade, but adds a frequency modulated capacitance probe (FMCP), to measure the difference in length between the longest blade and the other blades. The FMCP is attached to the mechanical probe and samples at speeds up to 30 kHz. The accuracy and durability of this probe are similar to the second generation probe; however, since all of the blades are measured, rotor-dynamics like eccentricity are detectable.

6.4.2.5.2   Capacitance

These sensors make measurements based on the electrical capacitance created by the gap between a blade of the turbine rotor and an electrode installed in the turbine casing. The turbine blades and disk must be electrically conductive or coated with some conductive material in order for this method to be feasible. These turbine blades are then grounded and capacitance is measured from the electrode in the casing. The capacitance is related to the distance between the blade and electrode as well as the common shared electrical area. The capacitance between the tip of the blade and the electrode in the casing is very small due to the small area of typical compressor blade tips and the relatively large clearances. This makes measurement very difficult by conventional means. In turbine applications, this capacitance is about 0.02 pF. A method of measuring capacitance indirectly by tying the capacitance level to a frequency modulated oscillator overcomes this difficulty. Thus, a change in capacitance drives a change in the frequency of the oscillator, which is processed by a demodulator and measured at high resolution. This measurement is then used to calculate a change in clearance by direct comparison to a calibration curve. Because of the significant decrease in capacitance with increased clearance, the combination of the electromechanical probe for coarse measurement and FMCP for fine measurements documented above is appealing. A static FMCP can measure tip clearance to within 60 μm (0.003 in.) over a range of 203 μm (0.00799 in.), increasing the ease of use and practicality of the sensor. In this sensor, the capacitance probe is rigidly mounted flush with the turbine casing or recessed into the casing. The capacitance and distance are still related by a calibration curve. In engine tests, the probe performed well in the high pressure compressor stage, but in the high pressure turbine stage, environmental effects – especially temperature – were too great on the electrical properties of the probe and measurements were invalid. The capacitance sensor only survived temperatures up to the goal of 1300°C for a short time period and therefore are not a reasonable choice for an turbine active clearance control. Another advance in capacitive sensor capability in measuring turbine blades is increasing the spatial resolution of the sensor by changing the geometry of the measurement situation, making better use of the electrostatic field around the sensor to better suit interaction with blade passages. Several capacitance sensors stacked together are used to increase lateral resolution of time-of-arrival measurements. Fabian et al developed a tip clearance sensor designed for active clearance control of a palmtop micro gas turbine. Since micro gas turbines spin at much greater speeds than normal turbines (optimal operating condition for the turbine in question is 800,000 rpm),

it is not feasible to measure tip clearances blade by blade. Thus, a capacitance probe was developed to use all of the blades as one electrode, and the entire casing of the turbine as the other. The capacitance between the two provides the average tip clearance for the whole turbine through a calibration curve. Fabian et al report excellent results of clearances within 1 μm (0.00005 in.) in a test situation [6.49].

6.4.2.5.3   Eddy Current Probes

There are two types of eddy current probes – active and passive. An active eddy current probe actually induces eddy currents in a target, whereas the passive probe allows target motion to induce Eddy currents through a static magnetic field. The disturbance caused by these eddy currents is measured in a conductive coil; when a blade passes, there is a peak in the voltage in the coil. The geometry of the measurement situation is important to the calculation of the disturbance in the magnetic field; however, any attempt to quantify this is neglected since the goal is to measure speed. The voltages are calibrated for each sensor, and electronics track the speed of blades. One advantage of an eddy current sensor is that it is possible to develop a sensor that operates without altering the engine casing at all. Such eddy current sensor is able of blade sensing through a turbine's casing without drilling holes. Eddy current probe should be able to withstand temperatures of 500°C, which may be sufficient for turbine use since the temperatures at the outside of the casing are significantly below the gas temperatures inside the casing. The mounting of the sensors in the engine might be carried such that they could operate under temperature conditions significantly lower than the peak temperature encountered in the engine section.

6.4.2.5.4   Optical Probes

Optical measurements of turbine blades are appealing because of the high speed of response and the resolution of measurements. The limiting factor concerning speed is the processing speed of the sensor. An optical method of measuring blade vibration uses optical fibers to measure reflections of a laser off of blades. The sensor is designed to detect the reflection of a laser off the tips of the blade in order to determine blade-by-blade time-of-arrival for use in vibration monitoring. The system is limited in resolution due to scattering of light off blades causing reduced power to be received back by the sensor. Vibrations in turbines can be measured using an optical system built on a semiconductor; this system also simply uses lasers to obtain time-of-arrival measurements in order to determine blade vibrations. Blade tip clearance can also be measured using two integrated fiber optic laser probes (IFOLPs) to detect the apparent width of a passing blade. The width of the blade changes linearly as the clearance increases due to the increased width of the laser spot relative to the size of the blade. Rather than attempting to measure clearance directly using lasers, apparent width of the blade tip correlates to the actual clearance. The two IFOLPs are angled so that one reflects off an incoming blade and the other off the outbound blade; the time interval between these measurements is used as the apparent blade width, which is correlated with blade clearance. The probe was tested on a NASA spin rig and was found to be accurate to within 13 μm (0.00051 in.) over a range of 2 mm (0.08 in.). However, this probe is suited only for the relatively safe environmental conditions of the compressor section of a turbine engine; any type of combustion materials or debris in the turbine section, along with the elevated temperatures decrease the effectiveness and survivability of the probe.

6.4.2.5.5   Pneumatic Probes

Air (pressure and flow) can be used as a non-contact method of measuring displacement and orientation. Many different types of sensors that measure how fluid flow is disrupted or interrupted by the passage of objects are available. One such example that might be applied to turbine blade passage is a sensor having an input and output port for pressurized air; in between the input and output is a hole for flow into the inside of the turbine. A blade passage partially and periodically blocks the flow into the turbine, and this is detected at the output of the sensor.

6.4.2.5.6   Microwave Systems

The sensor used in the microwave blade tip clearance measurement systems can measure changes in a microwave resonant cavity or can be phase-based like most modern radar systems [6.50]. In the phase-based microwave blade tip clearance measurement systems the microwave sensor emits a microwave signal that is reflected off of a target – a turbine blade. The returned signal is compared to an internal reference signal, and changes in the phase between these signals directly correspond to changes in the displacement of the target. The phase is determined by the distance traveled by the reflected signal relative to the distance travelled by the reference signal. Microwave-based sensor are designed to operate in temperatures up to 1400°C with a resolution of about 5 μm and bandwidth up to 25 MHz. The sensor can effectively operate in dirty environments and has the ability to see through oil, combustion products, and other common contaminants [6.51]. Turbine tip clearance measurement has been demonstrated with microwave sensors by Vibro-Meter. However, the system requires further refinement in order to be implemented in a flying engine but the effort is considered as achievable within the next three years. RF, microwave, optical or capacitive is foreseen as principles of detection of the tip clearance in a turbine. The expected performances of the sensors are: 2.5 mm range, 25 μm resolution, min 50 kHz bandwidth.

6.4.2.6   Torque

Torque sensors are usually base on the magnetic measurement principle but they make use of a calibrated section of a shaft. Such sensors are available, but problems are encountered with their reliability and the drift from the calibrated point. Given the fact that the torque on the shaft is same on ample sections, the location of the sensors poses problems, but this is not critical. The generic environment conditions for such sensors are: 15 – 300 kPa, – 60°C to +150°C. Such sensors are in a very advanced level such that within the next three years, they should be available for implementation to estimation of the thrust of the propulsion system. They are capable to measure torques of 10,000 to 20,000 Nm at frequencies of up to 10 Hz with 2% resolution.

6.4.2.7   Position/Arrival Time

Such measurement is necessary in active vibration control. The relative position of the blade with respect to where the blade should be located is the main concern of the detection. The tip clearance sensors could be used for this type of application and the measurement principle could be also used with some caution given the fact that the microwave sensors perform a distance measurement. Appropriate algorithms may facilitate the imaging of the blade arrival time and the resulting information be used for the active control of the blade induced vibration [6.52]-[6.54]. Other measurement principles have been proposed but the detection of the blade arrival time is limited to the following principles: capacitive, inductive, optical, microwave, infra-red, eddy current, pressure and acoustic. Such sensors should face the environment condition of the section, in which they operate. The applications for compressors are at TRL5, while the applications for turbine are in early stages of the proof of concept. Such sensors are expected to operate within a bandwidth of minimum 50 kHz.

6.4.2.8   Fuel Flow

The fuel flow control requires sensing within the burner vicinity. In more intelligent engine, each nozzle flow, or at least part of it, should be independently controlled in conjunction with the pattern factor and combustion instability control. Although the issue is of high interest, such systems are not commercially available or are not under commercial development for aerospace GTE. However, patents have been filed [6.55], which describe a fuel control system for gas turbine engines. The system includes logic that is used to facilitate enhanced

compressor stall margin when the engine is operating in potential icing conditions. The fuel control system is coupled to at least one fuel regulator within the engine, and receives input from a plurality of sensors coupled to the engine. More specifically, the system receives input from environmental sensors, as well as inputs representing compressor inlet temperature, compressor discharge pressure, and corrected core engine speed. The fuel control system also receives input from the other engine fuel regulators. However, the environmental conditions for sensor operation are quite rugged (300 – 4000 kPa, 700°C to 1700°C). Presently, there are little accomplishments in achieving such type of sensor. In March 2007 Precision Engine Controls Co. of San Diego CA, reported a new product, the eXVG intelligent gas fuel metering valve designed for use with large (up to10MW) turbines and reciprocating engines (up to 13,000 HP). Such a product is intended for power plants turbines. The operation pressure is max 35 bar gage, the volume flow of 5.5 l/hour to 5,500 l/hour is controlled while the reliability was tested for MIL specs. The operating range is –65 to +125°C. Such products that have been benefiting from both pull of the industry and the push of the research is a good example of technical advancement in gas turbine engines performance control.

6.4.2.9   Fuel Properties

Fuel properties may vary with the location of the fueling due to the variance in the refining process of various suppliers. It is common knowledge that the content of the fuel will significantly influence the performance of the engine. Presently, there is no means other than the standards provided by the suppliers to know the properties of the fuel. The concept of active adjustment of the regime based on the calorimetric properties of the fuel is a topic that is under discussion. Presently, fuel analysis can be performed in the lab [6.56] with dedicated equipment mainly for oil characterization. Spectroil M/N-W is the equipment used by the US Air Force at the time for fuel properties test. There is no known effort at this time to evaluate the calorimetric properties of the fuel during or after re-fueling and no measurement principle is presently known other than the laboratory based calorimetry.

6.4.2.10   Exhaust Gas Composition

The exhaust gas composition is of significant interest in the evaluation of the burning efficiency in conjunction with the fuel quality. The comments are same as in the above paragraph on the Emission Species detection. The environmental conditions for sensor operation are less rugged. However, spectrometry with portable equipment at 300 to 500°C is still of interest to the researchers and far form a commercial product.

6.4.2.11   Smart Sensors

Smart sensors are systems that exhibit certain level of compensation capabilities that enable them to perform self-diagnostics, self-calibration and adaptability. Meanwhile, smart sensors must carry computation capability that enable on-chip signal conditioning, be capable of non-significant data reduction and also be capable to detect and trigger selected events. Such type of sensors must be standardized for network protocol communication. The enabling technology that facilitates the intelligent sensors is the integration of the sensing element with the electronic circuit that supports the computation and communication software at the chip level. MEMS is enabling the realization of smart sensors. The intrinsic advantages of miniaturization that comes with reduced mass, reduced power consumption, high reliability and high integration levels is all achievable through MEMS Silicon technologies. However, the limitation associated with the carriers' diffusion in Si active components is expected to be overcome by the utilization of other semiconductor materials such as SiC and possible SiCN in building the electronic circuits. The SiC planar technologies for active circuits [6.57] represents a potential direction of research that it would enable realization of electronic circuits that could operate under higher steady temperature conditions and which would also facilitate the

realization of micro-electro mechanical systems capable to perform in very high temperature environment. As SiC is a semiconductor and research is going on towards refining the planar fabrication technologies of active SiC components (individual components such as diodes or transistors are already commercially available). SiCN has been synthesized from polymer based thermoset materials. However, only amorphous and small crystal phase has been achieved for SiCN, which makes it a ceramic material. However, this ceramic experiences super paramagnetic properties when blended with Fe or Fe ions [6.58]. Moreover, SiCN might be grown in larger crystals under specific conditions. The possibility to grow a single crystal of SiCN will enable the semi-conductivity of this material which might facilitate the realization of electronic circuits in surface technology.

The supra paramagnetic properties of SiCN doped with Fe opens also another potential avenue on realizing the basic material to fabricate spintronic electronics. This perspective is still distant but is feasible. Spintronics will become a common technology within the next 25 years or less, according to the amount of support in the fundamental and applied research in this discipline.

Conventional electronic devices rely on the transport of electrical charge carriers – electrons – in a semiconductor such as silicon. Now, however, physicists are trying to exploit the 'spin' of the electron rather than its charge to create a remarkable new generation of 'spintronic' devices which will be smaller, more versatile and more robust than those currently making up silicon chips and circuit elements. The potential market is worth hundreds of billions of dollars a year. Beyond, SiCN could stand very harsh temperature environment conditions.

6.4.3   Summary of Emerging Sensors

At the present time commercial sensors with integral electronics that could operate at temperatures higher than 115°C are scare or do not exist at all. Due to this limitation the majority of presently available sensors is performing the transducer task only.

To meet the future sensor requirements, new fabrication and material technologies, advanced sensing principles, and their potential applications to new sensor technologies are needed. MEMS is a good candidate to address the need for high-temperature operation and for new types of sensors, including smart sensor capabilities. Silicon-on-Insulator (SOI) provides some advantages (with potential operational temperatures of 300°C); the semiconductor SiC (up to 500°C) and the ceramic material SiCN (up to 1700°C) are explored for even higher temperatures. Several advanced sensing technologies are explored in combination with MEMS, including gas chromatography, spectroscopy and metal-oxide elements (electronic noses). Also wavelength Tunable Diode Laser technology is being explored for real-time measurements of important propulsion parameters, such as temperature, species concentration, pressure and velocity.

One of the major challenges to sensing at high temperatures is the electrical connection or wiring. Electric wiring technologies have remained almost unchanged, although some improvements have been made over the years in connections, insulation and electro-magnetic shielding technologies. Another significant bottleneck in the advancement of high temperature sensing is the pull component from the industry. A high production quantity based industry could be more persuasive than a quality production. Revolutionary technologies are adopted most of the times, when solutions, although often limiting or non-sufficient, are in hand.

The status of current R&D for new sensors (current TRL level) and future expectations (years to achieve TRL 6) will be summarized in a comprehensive table. Some examples on sensor requirements and the possible timetable for implementing advanced technologies for the various sensing variables are discussed in the following.

6.5 ROADMAPS

The above discussed sensors represent one possible scenario that may be followed by the development of sensors for the propulsion systems of the years 2025 – 2030. Although the requirements that need to be achieved in few circumstances look mundane, the accomplishment of any single item in the table below may require significant commitment form the user perspective and also from the researcher/developer side.

If one would consider all possible applications involving sensing, temperature sensing would come without any doubt in the first place. Temperature sensors that are capable to operate at high temperature are available and they have been developed for applications such as metal casting or such. Non-contact colorimetric measurements are also available but such optical based measurements require visual access to the hot area of interest. Besides, all such sensors might be incapable to perform within 5°C resolution at over 1500°C. Another aspect to consider is the measurement bandwidth, for example for temperature sensing for burner pattern factor detection and for turbine surface temperature monitoring. Thermal sensors to perform measurements within 0.1 second are challenging, and they are mostly associated with the miniaturization. This is one of the reasons, why the potential technology capable to yield such sensors is foreseen to be based on SiCN. Several research groups cover this research area. Dr. Rishi Raj and Dr. Victor Bright at the University of Colorado at Boulder are among the most active and advanced researchers. Other research facilities with SiCN research programs are listed in the following:

1) Institute for Materials Research (IMA), University of Bayreuth, D-95440 Bayreuth, Germany (Prof. Günter Ziegler).

2) Material Science Group at Cornell (Prof. Ulrich Wiesner).

3) Department of Fine Chemical Engineering and Chemistry, Chungnam National University, Daejeon 305-764, Korea (Prof. D.P. Kim).

4) Departamento de Ciências Naturais, Universidade Federal de São João Del Rei – UFSJ, Campus Dom Bosco, 36301-160 São João Del Rei – MG, Brazil, (Prof. Renato Luiz Siqueira).

5) Technische Universität Darmstadt, Fachbereich 11 – Material- und Geowissenschaften, Darmstadt (Dr. Emanuel Ionescu, Prof. Ralf Riedel).

6) ConCAVE Research Centre, Concordia University, Montreal, Canada, (Prof. I. Stiharu).

7) R&D Center for Special Inorganic Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 200050, P. R. China (Prof. Xiaofeng Peng).

8) Department of Chemistry, Graduate School of Science, Osaka City University (Prof. Matzumi Itazaki).

9) CFC key lab of National University of Defense Technology, Changsha, 410073, Hunan, People's Republic of China (Dr. Yi-He Li).

10) Center for Solid State Science, Arizona State University, Tempe, Arizona 85287 (Prof. P.A. Crozier).

The family of the pressure sensors identified has to cover a very large range of measurement, ranging form 15 to 4000 kPa with resolutions as low as 0.25% and bandwidth ranging from quasi-static to 40kHz. The temperature that such sensors will face is according to the section of the engine in which they have to operate. The pressure sensors that have to operate in temperature environment exceeding 750°C are not existent. The pressure sensors capable to operate in environment with temperatures from 250°C to 750°C use piezoelectric principle of measurement and therefore cannot measure static pressure, however are mature

enough to be used in GTEs during flying missions. Sensors that operate in environment with temperatures below 250°C are largely available. The family of sensors that must operate in extremely harsh environment is foreseen achievable mainly through the development of sensors from highly refractory materials including SiC and SiCN. As SiC is a semi-conductor, the development involving planar fabrication of electronic circuits on such material is ongoing. Single components are already commercially available through CREE Corp. [6.59]. Smart sensors based on SiC technologies are foreseen to be largely available by 2015. As SiCN is a ceramic material, the electrical properties should be induced through material doping. A huge spectrum of properties could be created through the present SiCN technology. However, sensors and mainly pressure sensors are not foreseen as available earlier than 2020. Fundamental research in SiC is ongoing for more than a decade and a half, while the applications of SiCN have been under investigation over the past 5 years or so.

Vibration is usually measured by accelerometers. The main type of accelerometers presently used is piezoelectric which could face significantly high temperatures (up to 750°C). However the integrated MEMS accelerometers include the electronics, therefore they can stand only a limited temperature range. Extension of the MEMS principles in conjunction with SiC and SiCN might significantly extend the capability of such systems to operate at high temperatures. Presently the condition monitoring of the turbine is carried out through a complex analysis from data collected by accelerometers located on the turbine external housing (Turbine Rear Frame). The timeline for SiC and SiCN technologies applied to micro-accelerometers follows the same frame presented above [6.60].

Emission species and exhaust gas composition sensors are largely available for the test rig measurements. The measurements are based on gas species detection through the analysis of the energy produced by the reaction of the targeted species when the gas is energized by specific means. Spectrometry provides the most accurate detection of species while metal-oxide based gas sensors (electronic noses) just commenced to become known in the field. The accuracy of the detection for spectrometry is somewhere in the range of 0.1-1 ppb, depending on the type of gas, while the metal-oxide sensing can reach less accurate levels equivalent to 0.5-1 ppb, also dependent on the type of gas [6.61]. Improvements in the performance of such sensors are expected to be achieved through the nanotechnologies. Nano-sized particles exhibit much higher surface properties than bulk base properties so they might be quite appropriate for the gas detection [6.62].

The high temperature operating sensors have the same challenges: the existence of an appropriate material that could be used for both sensor substrate and for the conductors [6.63].

Tip clearance and position/arrival time sensors have been demonstrated on capacitive and microwave principles. The sensors can operate in temperatures as high as 600°C [6.64], [6.65], while for higher temperature ranges up to 1700°C, the timeline of development for such sensors is given by the timeline of the development of SiCN based sensors in general. This is 2020 or later.

Torque sensors are largely available, and the required ranges of measurement and resolution to evaluate the real time thrust of the engine are implemented in few classes of engines (helicopter turbine engines). The existent technology [6.66] needs to be integrated in specific designs, although improved smaller sized sensor development is still ongoing. The timeline for such type of sensors is 2010, since they have to operate under normal temperature conditions (below 150°C).

There are three types of sensors with an apparent need in the future adaptive distributed control propulsion systems: fuel flow sensors for thrust estimation, gas flow in the gas path for the same purpose, and sensors for determination of the fuel properties. While the challenge is very much different for each of the three types of sensors, they have a common ground: there is no present work to cover this need at this time. Gas flow sensors are available, but they interfere with the continuity of the flow path. The fuel flow sensors are required to operate

close to the burner's nozzles, so the high temperature operation requirements apply to it. General speaking, such sensors might be available to operate under normal temperature range and also for much larger resolution range. Sensors for the measurement of fuel properties are unknown, since it is virtually impossible to relate the chemical structure of the fuel with its caloric capacity. Such sensors are seen as micro-calorimeters that could sample from the used fuel to evaluate the calorimetric properties of the fuel. The challenges to accomplish such type of sensors are significant, and they are estimated not to be available before 2020.

A comprehensive table including in a synthetic manner all the above requirements and the possible timetable is provided in Table 6.5.

Table 6.5: General Requirements, Present TRL Level and
Years to Achieve TRL6 for Future GTE Sensors

Generic Sensor Requirements and TRL							
Sensed Varible	Sensor Operation		Application	Technology	The technology level	Year to achieve TRL 6	Challenges
	Environment	Requirements					
Temperature	700 - 1700°C	± 5 C accuracy, < 1 Hz bandwidth,	Burner patter factor	thermocouple	TRL3	2020	Life, accuracy
				SIC detector, SICN detector	TRL2	>2020	accuracy/drifting, life, packaging
		resolution 5°C , 0-10 Hz bandwidth	Surface temperature turbine stator: turbine cooling (less than 1 Hz); life extending control (2-10 Hz)	SIC detector, SICN detector	TRL2	>2020	Integration with the blade, accuracy, life
Pressure	15 - 106 kPa, -60°C to +65°C	pres. +3 bar, res. ± 0.1%	Active inlet control	multiple technologies, integration possible	TRL3	available	the challenege on the case mounting and the high resolution
	15 - 106 kPa, -60°C to +65°C	res. ± 0.25%, 500 Hz bandwidth	Inlet distrosion control	multiple technologies, integration possible	TRL3	available	the challenege on the case mounting
	15 - 1800 kPa, -60°C to 500°C	35 kPa dynamic, ± 0.2% resolution, 5 - 40 kHz bandwidth	Stall margin management	lower temperature range existent sensors, higher temperature range, SIC	TRL3	2015	case mounted, high temperature variation may pruduce drift beyond the resolution, necessary compensation, the bandwidth requires miniaturization
	15 - 1800 kPa, -60°C to 700°C			SICN sensor/ electronic circuit embedded, SICN/Fe wires	TRL2/TRL1	>2020	high temperature requirements for the sensor and the electronics
	15 - 1800 kPa, -60°C to 500°C	35 kPa dynamic, ± 0.5% resolution, 1 Hz bandwidth	Active surge control	lower temperature range existent sensors, higher temperature range, SIC	TRL3	2015	Integration within the compressor
	15 - 1800 kPa, -60°C to 700°C			SICN sensor/ electronic circuit embedded, SICN/Fe wires	TRL2/TRL1	>2020	Installation in air-foil
	300 - 4000 kPa, 700°C to 1700°C	10 kPa dynamic, ± 5% resolution, 1000 Hz bandwidth	Combustion instability suppression	SICN sensor	TRL2	>2020	high temperature requirements for the sensor and the electronics

Vibration (accelerometer)	15 - 300 kPa, -60°C to +65°C	3%, 40 kHz, 1000g range	Vibration monitoring fan	already available, multiple technologies	TRL5	available	integration and data interpretation
	300 - 4000 kPa, 700°C to 1700°C	3%, 40 kHz, 1000g range	Condition monitoring turbine	lower temperature range existent sensors, higher temperature range, SiCN	TRL2	>2020	high temperature requirements
Emission Species	300 - 4000 kPa, 700°C to 1700°C	COx, NOx, 5% resolution, 5 Hz bandwidth	Emission control	available for low temperatures	TRL2	>2020	Installation in the HPT
Tip Clearance	15 - 1800 kPa, -60°C to 700°C	2.5 mm range, 25 μm resolution, 50 kHz	Compressor tip clearence control	microwave sensors	TRL5	2010	case mounting, miniaturization
	300 - 4000 kPa, 700°C to 1700°C	2.5 mm range, 25 μm resolution, 50 kHz		capacitive	TRL1	>2020	case mounted
Flow	15 - 300 kPa, -60°C to +150°C	1% resolution, 1 m/sec min flow	Thrust estimation	unknown	TRL0	unknown	interference with flow path
Torque	15 - 300 kPa, -60°C to +150°C	10.000-20,000 Nm, 10 Hz	Thrust estimation	phase shift, bearing thrust in the gear box, strain gage	TRL5	2010	Integration
Position/Arrival time	15 - 1800 kPa, -60°C to 700°C	capacitive or inductive, 50 kHz	Active vibration control	microwave sensors	TRL5	2010	Integration
				capacitive sensing	TRL1	>2020	high sensitivity
Fuel Flow	300 - 4000 kPa, 700°C to 1700°C	1 % resolution, > 6 Hz bandwidth	Mass fuel flow	capacitive/unknown	TRL0	unknown	resolution, high temperature operating environment
Fuel Properties	300 - 4000 kPa, 700°C to 1700°C	±0.5% resolution, quasistatic	Energy flow	micro-calorimetric heating value	TRL0	unknown	micro-calorimetry method and device
Exhaust gas composition,	20 - 200 kPa, 300°C - 500°C	1% resolution, quasistatic	Condition of the burner	spectrometry	TRL2	>2020	small size

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6.7   ACKNOWLEDGEMENTS

Chapter 7 – ACTUATOR REQUIREMENTS AND ROADMAPS

by

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ABSTRACT

The actuators requirements identified previously are reviewed, and the requirements of the three main application areas of flow manipulation, flow switching and mechanical manipulation are addressed. The requirements associated with the principal gas path components are considered and presented in a summary table derived from Chapter 2. The issues and considerations which must be made in the choice of any actuator for a specific application are reviewed followed by an assessment of available actuators and their application to the identified applications. The chapter is completed with a table of the applications, actuator specification, time to maturity and expected challenges.

7.1 INTRODUCTION

Whilst considerable developments have already been made towards all aspects of the more intelligent gas turbine, actuation is considered to be the most problematical and yet seems to have received the least attention. The compromises involved with the design of a gas turbine are well understood, although the exact control requirements and expected benefits still require definition. Sensor methods offer considerable challenges, but involve the transduction of low amounts of energy which greatly simplifies the methods. Sensors have been produced for engine development purposes for many years, which has helped to move the technology towards a stage where in-service applications might be considered. Control methods have not been extensively investigated. They are largely an extension of available methods, although the hardware required to implement them has severe environmental challenges. In contrast, actuation involves the transduction of relatively large amounts of energy and although the basic methods are understood and available for many of the identified functions within a gas turbine, there has previously been little incentive to develop them for similar environments to those encountered within a gas turbine. As a result, actuation within a gas turbine has largely been limited to the five main variables of fuel input, variable guide vanes, bleed valves and variable geometry intakes and nozzles. First generation tip clearance control using casing temperature has also recently been added. The actuators themselves have followed largely conventional lines using hydraulics for high force applications and electromechanical methods for low force applications such as valves, etc. Even so, they are also limited to the relatively benign areas, predominantly as a result of temperature considerations. As a general rule, the most productive areas for actuation improvement have been identified as the most challenging environments within the engine such as the high pressure turbine. Figure 7.1 shows the extremes of the environment, it is clear that all but the most robust actuators will be precluded from some areas. Initial applications are likely to be limited to less demanding areas.
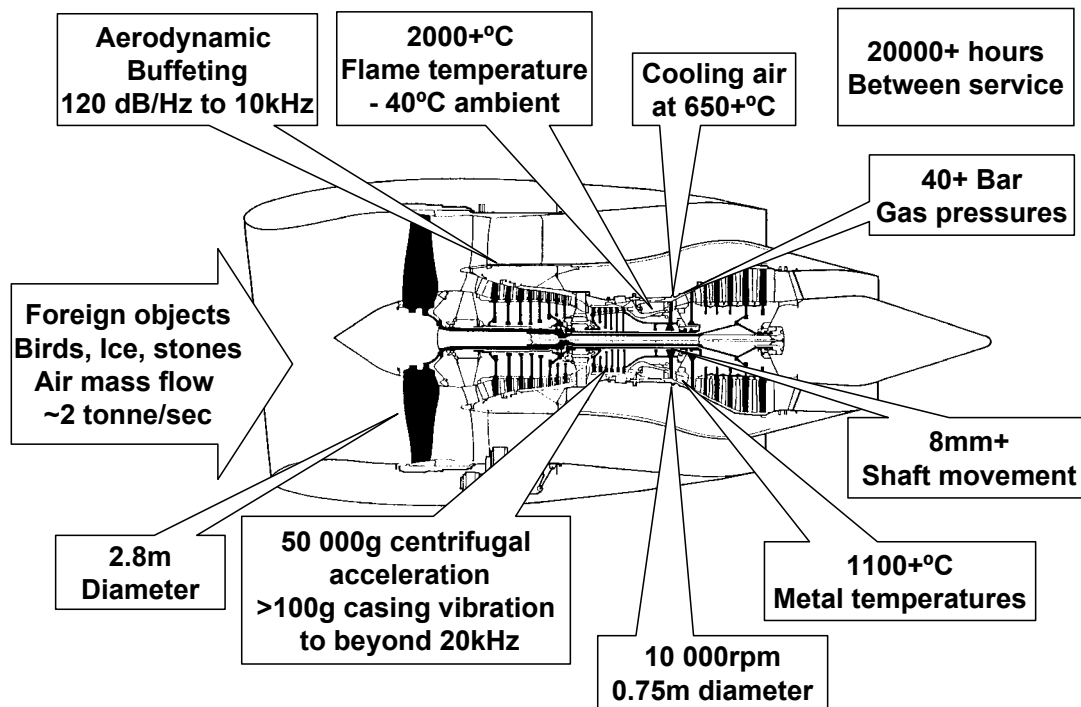
Figure 7.1: Environment within a Gas Turbine.

The new and emerging actuator technologies offer the potential to provide extended applicability and other requirements such as improved weight, reliability, cost, environmental impact, etc., but in order to address the requirements identified in Section 7.2, considerable developments will be required. Although this report is limited largely to gas path control, considerable enhancements of other areas of the gas turbine will also be possible in the future from these technologies.

7.2 BACKGROUND

Three common requirements can be identified for the entire gas path; these are flow manipulation, large scale flow switching and mechanical manipulation. Requirements for these three common functions have been identified for each element of the gas path and are discussed later in Section 7.5. The generic requirements are presented here and summarised in Table 7.1.

Table 7.1: Generic Actuator Requirements

Generic Actuators Requirements			
Actuator variable	**Actuator Operation**		**Notes**
	Environment	Requirements	
Microscale airflow manipulation	15-105 kPa, -60 - 55 C	Bandwidth and mass flow (1-2% of the core flow)	inlet flow control
	15-105 kPa, -60 - 55 C	15psi differential, < 10kHz	Inlet noise control
	15-1800 kPa, -60-800 C	Fast actuation < 4ms, pulsed jets; Bandwidth for all control variables – by W, source form Sanjay a) 200-300Hz, b) 5-20kHz, c) 50-100kHz; total <.5 % of core flow	Compressor surge control
	0-800 kPa, -60-150 C		Compressor flow control
Large scale flow switching	15-105 kPa, -60 - 55 C	Flow control bandwidth, input from W	Fan stall control
	0-800 kPa, -60-150 C	steady-state, up to 2% of core flow	Compressor stator vane flow control
	Up to 1800 kPa, 800 C	1-5 rad/sec bandwidth, 20% modulation of base-line cooling flow	Turbine cooling flow control
	20-200 kPa, 300 – 500; Hugo to pro-vide with aug-menter	1.5% of core flow per degree of vector angle	Thrust vectoring control
Fuel flow control	Fuel system pressure, -60-500C	high-band width actua-tion, typically greater than 500Hz to 1000Hz fre-quency range. Fuel flow modulation goal at 1 - 5% of mean flow	Combustion instability control
	Fuel system pressure, -60-700C	Schedule on emission sensing Fuel flow modulation on each nozzle at 1-5 rad/s	Emission control
	Fuel system pressure, -60-700C	Fuel flow modulation on each nozzle at 1-5 rad/s	Pattern Factor Control
Geometry control	15 - 105 kPa, -60 - 55 C	Geometry bandwidth control 15-20 rad/s,	
	15-105 kPa, -60 - 55 C	< 8mm deflection, < 0.5Hz	Inlet noise control
	0-800 kPa, -60-150 C	< 10Hz, 20 degrees	inlet guide vane for surge control
	0-800 kPa, -60-150 C	1-2 Hz	vane geometry/shape
Misc	15-1800 kPa, -60-700 C	Thermal, mechanical, pneumatic devices; Actuation > 0.1mm/s (1.5 Hz); Force 10kN; Stroke 3mm; Resolution 0.02 mm	Compressor clearance control
		pressure > 3000 N/cm²; deformation > 0.5mm; installation in airfoil; bandwidth? W	
	15-1800 kPa, -60-700 C		Compressor blade vibaration control
	Up to 1800 kPa, 700 C	Actuation > 0.1mm/s (1.5 Hz); Force 10kN; Stroke 3mm; Resolution 0.02 mm	Turbine tip clearance control

7.2.1   Flow Manipulation

This generally involves manipulation of the boundary layer within the main flow of the engine and can be either mechanical effects such as turbulence inducers, roughened surfaces or shock control bumps, etc.,

or aerodynamic control which involves blowing or sucking air through the component surface in order to affect the bulk flow, generally via the boundary layer.

Some programmes have investigated flow improvements using passive means and there have been proposals for active systems [7.1], but the author is not aware of any research for gas turbines.

Continuous blowing and sucking have been used in airframes for many years, largely to provide flow stability and increased lift under extreme conditions. Several studies have concluded that similar effects within a gas turbine would require too much air flow due to the high momentum transfer requirements. Developments for airframe applications over the last 10 to 20 years have shown the benefits of modulated sucking and blowing to provide increased effect or reduced energy input. The currently favoured method seems to be synthetic jets where a volume of air is drawn in slowly from the main flow, followed by rapid expulsion through the small orifice. Several mechanisms have been used and systems have been flown in programmes such as the XV15 experimental tilt rotor [7.2]. Recent work [7.3] for gas turbine applications has concluded that synthetic jets are unlikely to provide sufficient momentum transfer to give effective control within a gas turbine, so modulated jets seem to be the preferred option.

A generic requirement for multiple modulated jets applied through holes typically of much less than 1mm has been identified. Dependent upon the application, these can be required at a spacing of only a few millimetres. The majority of work on jets is investigating the use of jet frequencies which are matched in some way to a characteristic frequency related to the flow, although there seems to be no agreed method of defining this frequency or the relationship of the actuation frequency to it. This approach implies that each micro jet must have some form of sensing, decision making and actuation, potentially a massively complicated system. There has recently been suggestions that in some airframe applications it may be possible to use a fixed frequency for restricted applications [7.4]. Since the operation of a gas turbine is largely predictable, it may be possible to use this approach in order to use a fixed frequency, self excited jet modulator, allowing a much simplified system which can be turned on simply by supplying air to it.

7.2.2   Large Scale Flow Switching

Large scale flow switching has been identified as a requirement for applications such as stall/surge control, handling bleeds, cooling flows and STOVL. Several low speed valves have been developed around these applications and of course are already in service for handling bleeds. Large scale air injection for stall/surge control has achieved a status of a holy grail of advanced engine control. Several studies over the last 20 years have concluded that although sensing and control for this application are difficult, high speed actuation is the limiting factor. Despite several short term demonstrations, no solution for long term service applications has been achieved.

7.2.3   Mechanical Manipulation

Mechanical manipulation is well established for intakes, Variable Guide Vanes (VGVs) and nozzles. First generation tip clearance control systems using thermal casing expansion manipulation are also established, they give some improvement over passive methods, but are recognised as severely limited when compared to an ideal system. The requirements for each application vary considerably, particularly in the temperatures over which the systems must operate. Virtually all systems currently use hydraulics, although electromechanical systems are also now available. Many actuator systems have been investigated, some giving significant weight advantages, but the usual issues of temperature and reliability seem to be limiting progress.

7.3 OVERVIEW OF REQUIREMENTS AND CURRENT CAPABILITIES

Each section of the engine will be handled in turn.

7.3.1   Intakes

Variable geometry intakes largely rely on conventional hydraulic actuators. Some electrical devices are also used. These devices provide generally efficient actuation, but the mechanisms are limited and require significant aerodynamic compromise, with rigid surfaces, steps and gaps from the hinged surfaces. Weight of the overall system and high maintenance costs are also significant issues.

7.3.2   Fans and Compressors

Variable guide vanes are almost exclusively controlled by hydraulic or fueldraulic mechanisms. Bleed valves again use hydraulic systems, both systems now use electromagnetic control valves, although fluidic control has been used in the past.

7.3.3   Combustors

Fuel input was the first control input employed in a gas turbine, today's actuators are an efficient series of valves, using a combination of solenoids and hydraulic control.

7.3.4   Turbine

Due to the harsh environment, actuation within the turbine has only recently been achieved. Even now, it is limited to first generation tip clearance control systems. These use casing temperature control to shrink the whole casing. Since this is a relatively slow process, only simplified control can be achieved, although broader application has been limited by patents [7.5] and lack of development.

7.3.5   Reheat and Exhaust Nozzle

Nozzle control for re-heat is probably the most demanding actuation process in current engines. The high forces, rapid response time, high temperatures and vibration environment are accommodated to provide a very effective system, albeit at the expense of high construction and maintenance cost.

7.3.6   Other Applications

Other applications such as helicopters and STOVL have special requirements, but are not considered here.

7.4 TECHNOLOGY CHOICE

7.4.1   Requirements and Assessment

Actuation can be considered as a method of changing some physical parameter. In its purest form, this is simple mechanical movement either in translation or rotation. Actuation within a gas turbine however requires capability well beyond this simplistic view it must consider the interaction with the engine cycle such as the effect on air flows, combustion temperatures, etc., and must consider integration into the engine components.

The starting point of any survey must be to understand the actuation requirements, followed by evaluation of simple transduction method to provide movement or force to affect this change.

Comparison of the various transduction methods can be a complex process. The prime considerations must include the basic technical requirements of:

- Maximum force;
- Energy density;
- Stroke;
- Speed/repetition rate;
- Input energy type;
- Resolution/controllability;
- Support system requirements; and
- Environment limitations, e.g. temperature.

In addition, business and support issues must be considered such as:

- Cost;
- Service requirements;
- Environmental impact; and
- Ownership.

Numerous studies have reported comparisons of the many actuation techniques, however great care is needed in any interpretation of relative performance. It is quite common to see studies which are quite clearly biased to favour one particular technology, or where out of date data may unintentionally provide a misleading guidance. A further source of error may be where commercially sensitive data is not available to the researcher. One study which has striven to provide a comprehensive and impartial study has been carried out by Granta Designs Ltd during development of their materials selection database software [7.6-7.8]. Generally data was collated using information provided from published journals and conference proceedings. For example Bell DJ et al. compare 120 actuators gathered from existing literature on prototype devices [7.8]. Key mechanical properties (maximum force, maximum displacement, displacement resolution and maximum frequency) were considered. Due to the infancy of many smart actuation systems it can be assumed that a proportion of the data employed is generated from laboratory/prototype testing and not commercially viable solutions. This must be considered when making comparisons between the various smart actuation systems especially when using maximum values of an actuator's operational envelope. It is also evident that there may be some confusion between the transduction element and the overall system which may be needed to achieve actuation. For example, a hydraulic cylinder may appear to have a very good energy density, but when the full system including the pump and its driving mechanism, fluid reservoir pipes, etc., are considered, the weight will increase considerably. Hydraulics are however well established, very efficient and can be attractive in a high duty cycle and become more attractive when many cylinders can be actuated from a single pump. In comparison, Shape Memory Alloys (SMAs) have a very high energy density are intrinsically robust and require little support equipment, but they are slow and very inefficient, so are particularly suited to applications where infrequent use is required. Whilst hydraulics are well developed and established, SMA is still immature and only readily available in very small sections, often with variable properties.

This simple comparison highlights the difficulty in evaluating actuators for a particular application. The author is not aware of any study where the full implementation impact of actuation has been considered, even for established techniques. If the interest extends to new and emerging technologies, the comparison becomes more difficult. A thorough study including all aspects to produce a comprehensive comparison is urgently needed.

Some results from the Granta designs study are presented here to illustrate the key technology capabilities and current comparison methods. The capabilities of MEMS and Nano Electro Mechanical Systems (NEMS) are treated separately and shown in black on the charts, macro scale actuators being shown in green.

Figure 7.2 shows maximum force versus displacement. As expected, forces and displacements currently available from MEMS and NEMS actuators are lower than macro actuators. Smart actuators that require temperature change within the operational environment, such as shape memory alloys, are presented as exerting the largest forces (~ 5 N) of the MEMS actuators. Macro shape memory alloy actuators are claimed to offer only slightly higher forces at around 20N, however [7.9] presents results from an engineering component demonstrator using 6kN in a single piece of SMA. Clearly a significant limitation of the survey.
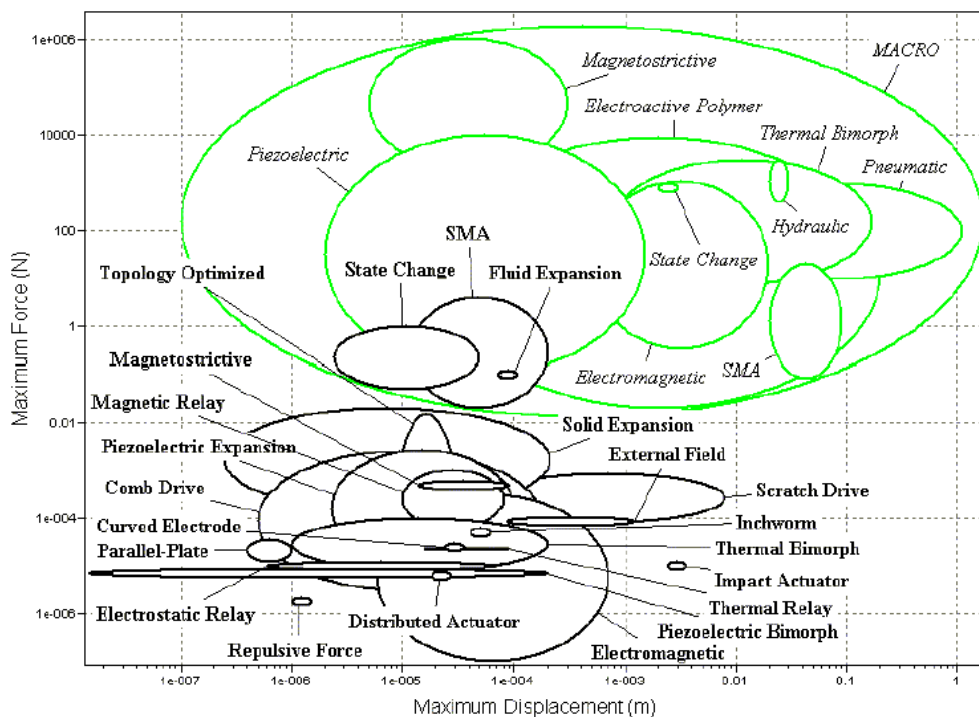

Figure 7.2: Maximum Displacement versus Maximum Force [7.8].

Figure 7.3 shows what is probably a more realistic method for mechanical property comparisons using stress-strain, which also provides energy density (MJ/m^3). This is a much more convenient method, giving the fundamental properties, but cannot take account of size limitations. Similar plots to present frequency response and efficiency can also be produced to provide the fundamental properties. The study does however largely only cover the basic transduction technology, the full system requirements are not considered, which causes major difficulty fir an engineering evaluation.
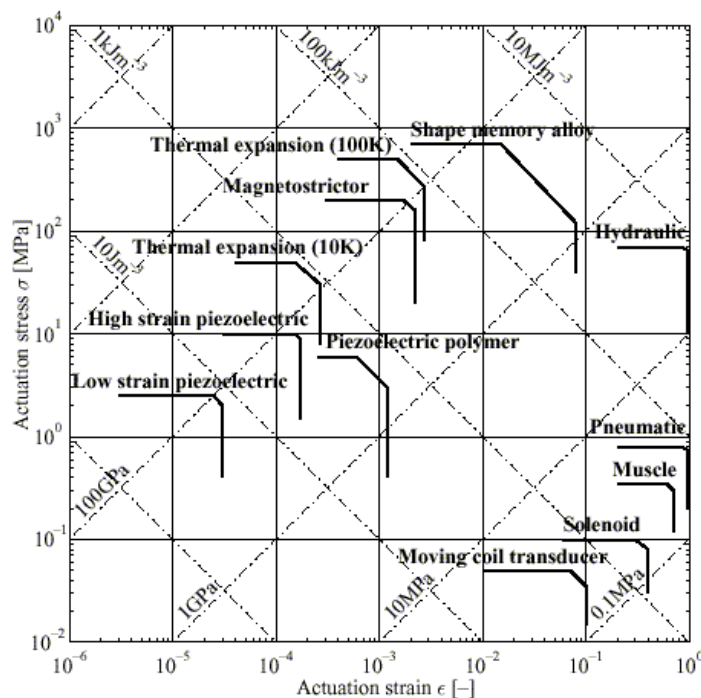
Figure 7.3: Actuation Strain versus Actuation Stress [7.7].

7.5 DEVELOPMENT REQUIREMENTS

As discussed earlier, each section of the engine already has some level of actuation. These largely rely on well established technologies. Although many studies have been carried out into new technologies, some have resulted in experimental engine tests, but very few have found their way into production engines. The requirements and limitations have been considered at an application level, there seems to be no thorough systematic study of the overall potential for advanced actuation. Two thorough generic studies are required before logical development of new applications and technologies can be achieved. These are:

- Application evaluation with performance, etc., benefits and actuator specification. This is essential to identify the most productive areas for application development and to produce an actuator specification.

- Technology evaluation, to identify the current capabilities and likely future developments including future system requirements, costs, maintenance, failure modes, etc.

Proposals for initial evaluation of existing and some emerging technologies are included below.

7.5.1 Identified Technologies for Future Developments

7.5.1.1 Established Technologies

Although potentially overlooked in the rush to newer and emerging technologies, the established actuators such as hydraulics, electrical and even fluidics still offer considerable opportunity for future developments. Opportunities to develop higher temperature and miniaturisation capabilities should be pursued. This will enable extended and distributed opportunities to be realised.

7.5.1.2   New and Emerging Technologies

A selection of the more promising emerging technologies are discussed here. Many of the technologies have been demonstrated at a laboratory scale, but development towards practical engineering applications suitable for large scale gas turbine applications is still lacking. The discussion must however be at a generic level, since the detail is far too extensive for this summary document. The prime requirement is to move the capabilities towards actuators which can be utilised in practical gas turbine applications.

7.5.1.2.1   Electroactive Materials

This class of materials produces strain in response to an applied voltage, and includes piezo electric ceramics, Electro Active Polymers (EAPs), etc. They offer very simple, highly efficient electrical actuation with minimal current, but require high voltages to operate. Although available for many years, the broader potential still requires considerable development.

7.5.1.2.2   Piezo Electric Ceramics

Current piezo devices are well established in general use and dominated by Lead Zirconate Titanate (PZT). This is very effective for many applications, but despite a higher Curie point, is limited to around 150°C for most practical work. Although limited in strain (~ 0.02%), very high forces are possible. Many mechanisms to provide higher displacements have been investigated, from simple lever mechanisms, through discrete flexural structures to fully integrated systems providing low stiffness flexing surfaces. These have potential for many gas turbine applications, but must largely be coupled to higher temperature developments. Alternative elements such as Lithium Niobate have been available for some time with a temperature capability in excess of 800^0C, but can only provide very small displacements. More recent developments have investigated a range of materials providing higher strain and improvements in the 150°C temperature capability. Development towards the identified applications should largely follow this route, preferably coupled towards specific applications. Mechanical amplifier development specific to identified applications are also needed.

7.5.1.2.3   EAPs

These are new, but can reportedly provide strains of up to 400%, albeit at very low stress. They are generating considerable interest for morphing wings due to their very high energy density, but are severely limited in temperature capability (~70°C). Some discrete actuator devices are also now commercially available. The author is not aware of any gas turbine specific developments, although applications within the intake and exhausts could be considered soon.

7.5.1.2.4   Shape Memory Materials

These materials generally react to changes in temperature in order to cause a movement. Although other inputs such as acidity, light, etc., are also possible, these are not yet sufficiently mature to be considered for practical applications. The temperature actuated materials are pre-set to a particular shape, to which it will attempt to return when activated. This can be used for a one-off assembly application, or as a repeated actuation. For the latter, a spring force is used to oppose the movement followed by movement in the opposite direction when de-activated.

Shape Memory Alloys (SMAs), are the most common, and have been commercially available since at least the early 1970s. The NiTi alloys now dominate although copper based alloys are also commercially available. Practical applications can achieve up to 8% strain for one-off assembly purposes, although 2% is a more practical limit for repeated applications in order to avoid premature fatigue failure. The one-way memory with

spring return to provide two stable positions is by far the most common in research programmes. A "two way" effect where bi-stable position actuation can be achieved within a single piece of material is also available, but with current alloys and methods this tends to provide less movement and be less stable. Continuous movement has been achieved in several programmes, but the high hysteresis causes severe difficulty and requires temperature controlled feedback. Development of the materials and applications has been dominated by the medical market, so has largely been limited to small sections of relatively low temperature materials, 150°C being a practical limit. In order to provide any high authority actuation, a relatively large section is needed. These are not readily available, and basic limitation of the roughly 50Ni50Ti materials suggest that consistent properties across large sections are unlikely to be achieved. 60% Ni materials have been investigated as a method of providing increased stability and versatility, but are not extensively reported in the literature. Alternative alloys with higher temperatures have been investigated, with operating temperatures approaching 900^0C reported, but are far from commercial availability. Development of these will be essential if the identified applications within the gas turbine are to be achieved.

Shape Memory Polymers can achieve much larger strains, but seem to be limited to assembly applications. Reports on re-lining of water pipes claim great success. Shape Memory Ceramics have similar properties and offer much higher temperature capabilities albeit at lower strains, they have been proposed for high temperature assembly purposes, but seem to have attracted relatively little research.

7.5.1.2.5   Magnetic Strained Materials

The magnetostrictive effect has been known in Nickel alloys for many years. An applied magnetic field causes strain generally parallel to the lines of magnetic flux. More recently, the commercial alloy Terfenol D and others have been developed to provide greater strain, but even then, only around 0.04% strain can be achieved, it requires large magnetic coils to provide the field and is limited in temperature. Robust, large and small scale commercial devices have been produced. A realistic assessment of the capability for a full system is required. Further investigation into the potential for higher temperature materials seems to be rare, the available knowledge requires collation and assessment.

7.5.1.2.6   Magnetic Shape Memory (MSM)

Also known as Ferromagnetic Shape Memory (FSM) materials provide much greater strain ~ 8% by phase transformations in a similar manner to thermal SMAs, but again activated by a magnetic field. These relatively new materials are commercially available, but possibly only from one supplier (AdaptaMat in Finland). They seem to offer significant potential, but are limited to around 70^0C and have very low modulus which limits their effectiveness. The potential for higher temperature materials would be a very worthwhile activity.

7.5.1.2.7   Microsystems, Micromachines and Micro Electro Mechanical Systems (MEMS)

Although strictly having slightly different meanings, these are three terms are used for miniaturised actuator systems, often incorporating sensing and decision making. The basic transduction methods are smaller scale versions of larger devices, but the miniaturisation coupled to multiple manufacturing techniques borrowed from electronics methods provide significant potential advantages. The most widely known applications are for ink jet printer heads and automotive air bags. These exploit the small scale and very low unit cost of this technology. With the required production volumes anticipated for aerospace, it is widely considered that the very low costs are unlikely to be achieved, but the other advantages could well out weigh the cost considerations. As an actuator, the scaling effects produce some interesting results, where electrostatic forces become significant to the extent that practical actuators have been produced and the low strain of piezo electrics is a less significant

limitation. A plethora of small scale devices including valves, gear mechanisms and even an operating gas turbine with 5mm diameter rotor have been produced. The opportunities for multiple distributed systems, particularly for boundary layer manipulation, have been identified, although the provision of this within the constraints of damage tolerance, cost and maintainability have not been fully explored.

7.5.2   Other Technologies

The previous sections have considered the available and emerging actuator technologies which are likely to be developed in the near future. Others which have been investigated at an academic level such as local combustion effects, optically actuated polymers and vibration actuation are not yet sufficiently mature to consider in-depth development, but the future potential should be monitored and enhanced funding considered as appropriate.

7.6   ACTUATOR AND APPLICATION DEVELOPMENT REQUIREMENTS

Previous sections of this chapter have dealt with generic technologies and applications. The generic actuator developments have been considered in 7.0. The nature of actuator applications also requires application specific developments. The specific requirements identified previously are summarised in relation to engine components in Table 7.2.

Table 7.2: Application/Actuator Requirements

	Technology	Controlled Variable	Environ-ment	Special Requirements
Inlet	Control of Inlet Shock Position	Inlet geometry		
Inlet	Inlet Distortion Control	Vortex generator geometry, jet, suction		Pulsed micro jets
Inlet	Active Noise Control	Honeycomb geometry, acoustic waves		
Compressor	Active Stall / Surge Control	Jet, guide vane movement, bleed air	200°C	Fast actuation < 4ms, pulsed jets
Compressor	Active Flow Control	Jet, suction, airfoil geometry	-50 – 600°C	Fluidic actuation devices at different frequencies: a) 200 – 300Hz; b) 5 – 20kHz; and c) 50 – 100kHz. Shape memory alloys for airfoil shape variation. Installation in airfoil, robust design required.

	Technology	Controlled Variable	Environment	Special Requirements
Compressor	Active Clearance Control	Casing geometry	up to 700°C	Thermal, mechanical, pneumatic devices Actuation > 0.1mm/ms
Compressor	Active Vibration Control	Airfoil geometry	300-650°C	Pressure > 3000 N/cm² Deformation > 0.5mm Installation in airfoil
Combustor	Combustion Instability Control	Fuel modulation, acoustic energy, jets, moving surface	~ 1400 °C	High-band width actuation, typically in the l00Hz to 500Hz frequency range.
Turbine	Active Clearance Control	Casing geometry	~ 700°C	Thermal, mechanical, pneumatic devices Actuation > 0.1mm/s Force 10kN Stroke 3mm Accuracy 0.02 mm
Nozzle	Active Noise Control	Nozzle geometry, jets		Shape memory alloys

7.6.1   Inlet

7.6.1.1   Inlet Geometry

Variable inlet geometry has been accepted as essential for supersonic aircraft for many years and very capable systems developed. These are invariably hydraulically actuated. It is tempting to promote alternative methods of actuation, although none of the advanced technologies covered earlier seem to be capable of the high speed, high displacement actuation to provide a direct replacement. An alternative approach was used in the US research programme SAMPSON [7.10]. Boeing achieved a full size wind tunnel demonstration of an SMA actuated F15 intake with variable upper ramp and smooth shape changing lower lip. The prime limitations were however the low temperature SMAs leading to a slow cooling and hence retraction time and the availability of the SMA in wire form only, which necessitated an over complex, chain driven mechanism (Figure 7.4).
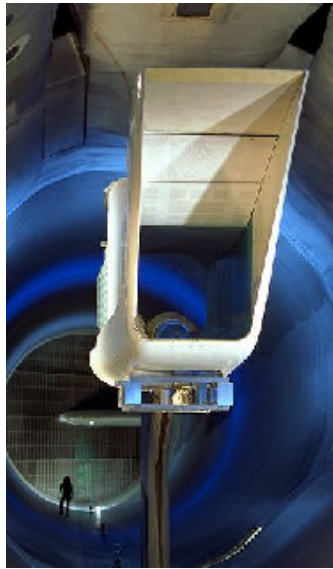
Figure 7.4: Boeing/SAMPSON Programme SMA Actuated Intake.

The programme also demonstrated a more ambitious compliant throat mechanism, replacing the rigid ramps with a flexible membrane and appropriate control mechanisms. This advanced thinking can be expected to give greater benefits, but also presents larger risks and development time.

Subsonic intakes can potentially use much slower actuation mechanisms for gross movement. A particular limiting factor being the need to accommodate cross winds and other off-axis flows, again, SMAs are a prime candidate, although simpler mechanisms such as air pressurised bladders may also be appropriate.

7.6.1.2   Inlet Distortion Control

The gross movements discussed in 7.6.1.1 will have a major impact on inlet distortion, but smaller scale actuation has also been demonstrated as significant. Boundary layer or shock wave manipulation in various forms has been investigated, but is still some way from a thorough understanding or practicality. The prime requirement is to provide a clean airflow to the fan whilst minimising the nacelle drag. In particular, the compromise between tolerance to cross wind and whilst maintaining a thin nacelle is particularly important on transport aircraft with ever increasing fan size. Similar requirements have also been identified to maintain a clean flow in S shaped ducts. The AEROMEMS programme [7.1] built on many years of international work and demonstrated the capability for boundary layer manipulation by modulated microjets and synthetic jets on aircraft wings and engine intakes. Other programmes [7.4] have identified alternative strategies and operational frequency ranges which have been picked up by programmes such as ADVACT [7.3]. Alternative methods such as moveable vortex generators and shock control bumps have also been investigated in several programmes.

It is clear that the fundamental fluid mechanics is not yet sufficiently understood to provide a definitive specification for actuators. The first priority should be in understanding the requirements. Despite this, many programmes have investigated actuator mechanisms to provide jets or small scale geometry changes, a few have been aimed at gas turbine applications. Emphasis should be placed on understanding the airflow characteristics, actuator specifications and moving towards full scale demonstration.
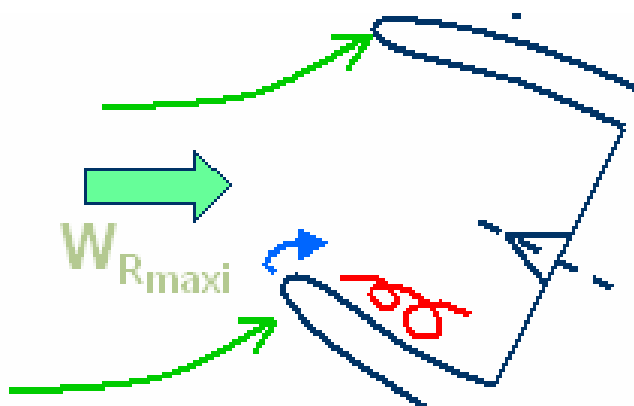
Figure 7.5: Intake Separation at High Incidence with Thin Intake Lip.

7.6.1.3   Inlet Noise Control

Three main regions for inlet noise control have been investigated; these are the overall geometry, adaptive surface noise treatments and active noise cancellation systems. For changes in overall geometry it is considered unlikely that additional complexity and weight could be justified to achieve noise control. Adaptive surfaces to provide optimised acoustic honeycomb by changes in acoustic impedance and resonance have been successfully demonstrated within the Silencer programme [7.11]. Provided these can be ruggedized and made suitable for routine use, this appears to be the most productive approach. Fully active noise cancellation systems have also been demonstrated, but again are likely to be heavy, complex and potentially expensive, making them less attractive.

7.6.2   Compressor

7.6.2.1   Compressor Active Surge Control

Active surge control has been an on-going goal for many years. The exact configuration, approach and response requirements have still to be defined, as have the conditions which must be accommodated. These range from very early detection of stall which can be identified as a pre-cursor to stall, to alleviation of the onset of a major surge. The initiation of stall is a much less aggressive phenomenon and can be controlled by a much lower authority actuator than early surge. The simplest form can be blade tip / casing boundary layer control systems which are scheduled to be activated when stall is likely to occur, through relatively slow (< 1 sec) bleed forward systems relying on advanced detection techniques, to major, high speed (< 40ms) bleed forward systems controlling large airflows. With some systems likely to need many millions of actuation cycles, actuator lifetime is a major limiting factor with current actuators.

With the high importance of this subject, a large scale collation of available techniques and data should be carried out as soon as possible and a coherent plan produced.

7.6.2.2   Compressor Active Flow Control

Flow control is required in a compressor to accommodate the wide range of conditions which are encountered across the full operational envelope. Considerable design compromise is required even with the current practice of using variable vanes and bleed valves. These compromises significantly reduce the design performance,

although the exact extent of lost efficiency is not widely reported. Active techniques are frequently identified as a very productive way forward.

The current mechanical systems of hydraulics, unison ring and levers are well established, but are also recognised as a source of reliability and cost issues. Alternative mechanical systems such as SMAs, piezo and distributed hydraulic systems have all been investigated, but none seem to have moved towards practical demonstration.

Airflow manipulation techniques such as boundary layer sucking and blowing have been known for many years. More recently, modulated blowing techniques have been raised as a more efficient possibility. It is clear that the aerodynamic requirements to achieve control are still not understood and must be clarified before larger scale demonstration can be achieved. The actuators themselves are also very immature, although several programmes have investigated MEMS devices providing appropriate characteristics. The preliminary specifications which are currently available should be sufficient to allow actuator development to continue in parallel with expansion of the airflow understanding.

7.6.2.3   Compressor Active Clearance Control

Considerable effort has been expended on turbine blade tip clearance control, with many concepts being developed, as exhibited by the number of patent applications made. In comparison, compressor tip clearance control has attracted very little attention. Although lower overall improvements are expected from compressors, the demands on any actuation system is far less demanding. In particular, the peak temperatures are in the order of 650°C in the higher pressure ratio engines and pressure differences across the stages are also reduced. Many of the techniques raised for turbines should be applicable to compressors, but must be achieved at lower cost and weight to reflect the lower returns achievable within the compressor. Recent developments of electromagnetic and piezoelectric actuators are bringing them into the temperature range of compressors and should be vigorously pursued. The mechanisms required to achieve smooth and efficient movement without introducing other loss factors such as leakage, steps and gaps may however prove to be a bigger challenge than the actuators themselves and must also be pursued.

7.6.2.4   Compressor Active Vibration Control

At the design stage, vibration alleviation of all aerodynamic components, particularly fans continues to require considerable design compromise. When this is further compromised by the requirement to accommodate changes due to FOD, improvements in blade and vane damping control offers the potential to provide significant performance improvements.

Investigations of passive blade and vane damping have been successful at the laboratory and rig stage, but few have yet to find their way into service. Active techniques using piezo patches have been developed for airframe applications such as the F18 tail fin, but are not known for engine applications.

Whilst significant benefits might be achievable, the emphasis previously placed on vibration control seems to be very low. The benefits and costs of any potential system should be fully evaluated before significant developments are initiated.

7.6.3   Combustor Instability Control

Recent developments towards lean burn methods for civil engines have shown considerable benefits, but have also exacerbated combustion noise issues which cause issues for community noise and potential fatigue of

other components. Similar issues might be expected within military engines. Active instability controls have been achieved in experimental engines, but the attributes of high authority, high freq and long life have been difficult to achieve. Numerous actuation techniques are available, although temperature may be an issue dependent upon their mounting position.

7.6.4　Turbine Active Clearance Control

As discussed previously, much effort has previously been expended in the pursuit of effective tip clearance controls. The leading technique is currently casing temperature control to shrink it towards the blades. This is a significant improvement over previous uncontrolled methods, but the ultimate goal of independent control at all circumferential points still seems to be a long way off. The prime limiting factor is the temperature. Successful actuator, sensor and seal mechanism development will be essential to achieve the ultimate goal. In the shorter term, less sophisticated techniques such as two stop and uniform circumferential positioning are likely to give significant advantages, but again will need significant developments.

7.6.5　Nozzle Active Noise Control

Geometrical jet noise reduction measures have been under investigation almost from the start of the jet era. Developments continue with the aim of reducing the jet noise without increasing drag or other inefficiencies. For civil applications, the chevron nozzle on the Rolls-RoyceTrent1000 / Boeing 787 is the latest of a series of developments. Experimental adaptive chevron nozzles using SMAs were flown as part of the Boeing / General Electric programme of the Quiet Technology Demonstrator 2 (QTD2) programme. Investigations of systems suitable for use in service are also under investigation. These systems could potentially be deployed in the relatively near term and should be pursued.

Chevrons are believed to work by interrupting the shear layer between the jet and the free air stream. Longer term options of aerodynamically causing a similar effect are under investigation. Although currently more speculative, these may cause less disturbance when not deployed and could be more attractive.

7.7　SUMMARY AND CONCLUSIONS

Enhanced actuation has been identified as potentially the most productive area for improving the performance and availability of the gas turbine, although the actual benefits have generally not been fully quantified. The first requirement is to provide an accurate evaluation of this potential and an outline specification for the actuator technology. Many base actuator technologies are available which have some capability towards the currently identified requirements, but in every case, limitations have been identified. The most significant of these is the operating environment which is far more aggressive than the vast majority of industries. Although generic requirements can be identified, developments towards these environmental requirements must be intimately coupled to the specific application requirements in order to satisfy the overall constraints. With the new technologies which will inevitably be introduced, issues which are well established for current technologies such as certification and supply chain will also require considerable developments.

The prime aim should be to move the technologies which have already been demonstrated at a laboratory scale towards practical applications.

Actuator applications to various components together with specifications, candidate technologies, current technology status, time to availability, and the challenges are summarised in Table 7.3. Estimated availabilities range from 2010 (for miniaturized electro-magnetic valves for fuel flow control and large-scale flow switching

for compressor stator vanes and pneumatic tip clearance control), to 2013/2018 (for micro-scale flow manipulation depending on operational temperatures) and 2020 (for high temperature shape alloys for turbine tip clearance control).

Table 7.3: Requirements for Specific Applications together with their Generic Specifications, Candidate Technologies, Current Level of Maturity, Time to Achieve TRL6 and the Challenges

Actuator variable	Actuator Operation Environment	Actuator Operation Requirements	Notes	Technology	Current TRL	Year to Achieve TRL 6 Goal	Challenge
				Generic Actuators Requirements and Roadmap			
Microscale airflow manipulation	15-105 kPa, -60 - 55 C	Bandwidth and mass flow (1-2% of the core flow)	inlet flow control	Pulsed micro jets	3	2013	Getting adequate mass flow for effective control
				Synthetic jets	3	2013	Getting adequate mass flow for effective control
				Mechanical microflaps	3	2013	Mechanical integrity
	15-105 kPa, -60 - 55 C	15psi differential, < 10kHz	Inlet noise control	pulsed microjets	3	2013	
	15-1800 kPa, -60-800 C	Fast actuation < 4ms, pulsed jets; Bandwidth for all control variables – by W, source form Sanjay	Compressor surge control	Pulsed microjets	3	2015	Adequate mass flow, durability, temperature
	0-800 kPa, -60-150 C	a) 200-300Hz, b) 5-20kHz, c) 50-100kHz; total <.5 % of core flow	Compressor flow control	Pulsed microjets	3	2018	Adequate mass flow, durability, temperature
Large scale flow switching	15-105 kPa, -60 - 55 C	Flow control bandwidth, input from W	Fan stall control	electromagnetic valve	4	2011	
	0-800 kPa, -60-150 C	steady-state, up to 2% of core flow	Compressor stator vane flow control	flow control valve based on electromagnetic/hydraulic/other	4	2010	Weight, reliability
	Up to 1800 kPa, 800 C	1-5 rad/sec bandwidth, 20% modulation of base-line cooling flow	Turbine cooling flow control	flow control valve based on electromagnetic/hydraulic/other	3	2014	temperature
	20-200 kPa, 300 – 500; Hugo to pro-vide with aug-menter	1.5% of core flow per degree of vector angle	Thrust vectoring control	flow control valve based on electromagnetic/hydraulic/other	3	2014	
Fuel flow control	Fuel system pressure, -60-500C	high-band width actua-tion, typically greater than 500Hz to 1000Hz fre-quency range. Fuel flow modulation goal at 1 - 5% of mean flow	Combustion instability control	magneto-strictive	3	2012	wieght, life, flow control control authority, temperature
				electro-magnetic	3	2010	weight, modulation frequency, temperature
	Fuel system pressure, -60-700C	Schedule on emission sensing Fuel flow modulation on each nozzle at 1-5 rad/s	Emission control	magneto-strictive	3	2014	
	Fuel system pressure, -60-700C	Fuel flow modulation on each nozzle at 1-5 rad/s	Pattern Factor Control	electro-magnetic			
Geometry control	15 - 105 kPa, -60 - 55 C	Geometry bandwidth control 15-20 rad/s,		Pressure	4	2012	Durability, level of control
	15-105 kPa, -60 - 55 C	< 8mm deflection, < 0.5Hz	Inlet noise control	Piezo electric	3	2012	Complexity, high movement
	0-800 kPa, -60-150 C	< 10Hz, 20 degrees	inlet guide vane for surge control	Electromagnetic	3	2012	Weight, response time, synchronisation
				Piezo electric	3	2012	Low strain, synchronisation
	0-800 kPa, -60-150 C	1-2 Hz	vane geometry/shape	SMA	2	2018	synchronisation, response time,
	15-1800 kPa, -60-700 C	Thermal, mechanical, pneumatic devices; Actuation > 0.1mm/s (1.5 Hz); Force 10kN; Stroke 3mm; Resolution 0.02 mm	Compressor clearance control	Pneumatic	5	2012	Stiffness, control
				Hydraulic	3	2015	seals, complexity, weight
				Piezo electric	3	2015	low strain, temperature
				Electromagnetic	3	2012	weigth, control
	15-1800 kPa, -60-700 C	pressure > 3000 N/cm²; deformation > 0.5mm; installation in airfoil; bandwidth? W	Compressor blade vibration control	Piezo electric	3	2015	Complexity, control system weight
				SMA re-tuning	3	2015	synchronisation, control, temperature
	Up to 1800 kPa, 700 C	Actuation > 0.1mm/s (1.5 Hz); Force 10kN; Stroke 3mm; Resolution 0.02 mm	Turbine tip clearance control	electro-magnetic	2	2018	Temperature, weight
				pneumatic	5	2010	two stop system only,
				hydraulic	2	2015	Temperature, working fluid, weight, reliability
				High temp shape memory alloys	2	2020	adequate control authority, proportional control, stability

7.8   REFERENCES

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Chapter 8 – SUMMARY AND RECOMMENDATIONS

by

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8.1   SUMMARY

Intelligent Propulsion Systems can potentially meet future challenges related to capability, affordability, safety, and environmental compatibility. The key enabling technologies for an intelligent GTE are:

1) Increased efficiencies of components through active control;

2) Increased overall engine gas-path performance and extended "on wing" life of the engine through model-based control and health monitoring; and

3) Reduced weight ratio of control system to engine through distributed control with smart sensors.

For these future capabilities sensor and actuator requirements were identified, current status and emerging sensing and actuation technologies were discussed, and roadmaps for developing the new technologies were developed. Chapter 1 provided an introduction of the report. A summary of the rest of the chapters including the major findings is given in the following.

Chapter 2 describes the various concepts of *Active Component Control* that 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. The report describes the following promising applications in detail:

Inlet: Active Inlet Control, Active Noise Suppression, Active Noise Cancellation

Compressor: Active Surge Control, Active Flow Control, Active Clearance Control, Active Vibration Control

Combustor: Active Combustion, Instability Control

Turbine: Active Clearance Control, Cooling Air Control, Active Flow Control

Nozzle: Active Noise Control, Adaptive Nozzles, Thrust Vectoring, Active Core Exhaust Control, Afterburner Stability Control

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 were outlined for each of the gas turbine sections from inlet to nozzle.

Chapter 3 discusses *Intelligent Control and Health Monitoring* concepts using advanced model-based Multi Input Multi Output (MIMO) control architecture, where all available control actuators are manipulated in a coordinated manner. This overcomes the limitations of state-of-the-art engine control and can also provide outputs for which sensors are not available, i.e. virtual sensors. These virtual sensors provide the capability to directly control unmeasured variables such as thrust and stall margin. For implementation it is necessary to demonstrate that the control model reflects the actual condition of the engine by using a "tracking filter" (which estimates model parameters related to deterioration) and that the model parameters adapt to the individual engines. The MIMO controller can be designed to meet the desired performance objectives and also lends itself to automated fault accommodation.

With increased performance of the on-board computer there is a recent trend to have a stand-alone, engine mounted Engine Monitoring Unit (EMU). Such an EMU has access to continuous data, powerful computing capability that provides on-board analysis, can process large volume of data which are impractical to transfer to the ground, and can look also for transient effect and accomplish this throughout the duration of the whole flight. On-board condition monitoring determines the general health of the engine (level of degradation or effective age) and detects and isolates sudden faults (related to sensor fault, actuator fault or component fault).

Adaptive models open up the possibility of adapting the control logic to maintain desired performance in the presence of engine degradation or accommodating any faults in a way such as to maintain optimal performance or trade-off performance with remaining useful on-wing life of the engine. The Model Predictive Control (MPC) is an emerging approach, which solves a constrained optimization problem online to obtain the "best" control action, based on a tracked engine model, constraints, and the desired optimization objective.

Requirements for improved and new sensors have been identified:

1) To improve model accuracy, reliability and enhance observability of virtual sensors;

2) To allow sensors at stations within the engine gas path that are currently not instrumented due in part to the harsh conditions including high temperatures; and

3) To allow additional monitoring of vibration, mass flows, fuel properties, exhaust gas composition, and gas-path debris.

The environmental and performance requirements for these sensors are summarized.

Chapter 4 discusses *Distributed Engine Control* using high temperature electronics and open systems communications will reverse the trend of increasing weight ratio of control system to total engine and also be a major factor in decreasing overall cost of ownership for aero propulsion systems. The implementation of distributed engine control is not without significant challenges, including needs for high temperature electronics, development of simple, robust communications, and power supply for the on-board electronics. Although no new sensors or actuators are needed to enable distributed engine control, there is a need for on-board electronics located on or close to the sensing element or the actuator, such that network communications can be enabled and the wiring harness required for communications between sensors and actuators and the engine controller can be substantially reduced. The location of the node will dictate the operating temperature requirement, which in some cases could be as high as 500°C. With the limitation of standard silicon technology to less than 125°C, newer material technologies are required. In the absence of sufficient temperature capability distributed architecture could still be implemented, but with a weight penalty for additional structure to minimize heat soak

from the engine. Another challenge for enabling distributed engine control is to supply the power needed for the on-board electronics – innovative power supply architectures and technologies will need to be developed to exploit the full potential benefits of distributed engine control.

Chapter 5 outlines *Universal Sensor and Actuator Requirements*. Even if the sensor and actuator technology meets performance requirements, there are still various hurdles to be overcome for the technology to transition into a real engine. Three broad areas for these "universal" requirements are discussed:

1) When a technology is being considered for incorporation onto/into the engine, the impact on revenue and cost and the ease of integration has to be evaluated.

2) Requirements (other than performance) are summarized that need to be met to consider a technology to be at a prototype level and ready for potential insertion.

3) The process of moving a product, process or component towards maturity is discussed.

It typically follows the development route as described in the Technology Readiness Level (TRL) definitions. Business, manufacturing, legislative, etc., issues must be covered at an appropriate level at all stages.

Chapter 6 discusses *Sensor Requirements and Roadmaps*. The standard GTE Gas Path Sensors are designed and packaged according to the specifications driven by the certification requirements to the aircraft and GTE and were mostly written by the GTE manufacturers following guidelines of MIL-STD 810F for tailoring sensors's environmental design and test limits to the conditions that the specific sensor will experience throughout its service life, and for establishing laboratory test methods that replicate the effects of environments on sensors. Specifications of the most of present sensors with integrated electronics are limited to environment conditions within –65°C to +115°C. Sometimes the temperature limitations can be overcome with integrally attached electronics that is installed in the GTE location with acceptable temperature. By changing the packaging and/or design features of the system some of the current sensors can be modified to meet higher then present operating temperature ranges. Operation environments of 750°C may be possible, which would meet requirements for sensors located towards the engine intake, compressor and in some cases low pressure turbine. For sensor locations closer to the engine combustion chamber or afterburner, sensors withstanding even higher temperatures (up to 1700°C) are required. Sensors for these temperature requirements do not exist. There is also a need for "smart" sensors, which would enable future distributed control architecture. In addition, a number of sensors, which are of interest for more intelligent gas turbine engines, are being explored or do not yet exist, for example the turbine emission species sensors, burning pattern factor sensors, fuel property sensors, and exhaust gas composition sensors. Meanwhile, rapid emerging technologies were made available during the three years duration of the Task Group, including tip clearance measurement technologies such as eddy current and microwave methods. Implementation of available sensors is an additional major issue. Sensors should be small, light, low cost, and reliable. Also embedding of the sensors within the structure of the engine is an issue that has been investigated by researchers, but has not been implemented in prototypes or even on military engines.

To meet the future sensor requirements, new fabrication and material technologies, advanced sensing principles, and their potential applications to new sensor technologies are being explored. Micro-Electro Mechanical Systems (MEMS) is a good candidate to address the need for high-temperature operation and for new types of sensors, including smart sensor capabilities. Silicon-on-Insulator (SOI) provides some advantages (with potential operational temperatures of 300ºC); the semiconductor SiC (up to 500°C) and the ceramic material SiCN (up to 1700°C) are explored for even higher temperatures.

Several advanced sensing technologies are explored in combination with MEMS, including gas chromatography, spectroscopy and metal-oxide elements (electronic noses). Also wavelength Tunable Diode Laser (TDL) technology, which is based on telecommunication-type devices operating in the visible and near-IR portion of the spectrum, is being explored for real-time measurements of important propulsion parameters, such as temperature, species concentration, pressure and velocity.

The status of current RandD for new sensors (current TRL level) and future expectations (years to achieve TRL 6 (prototype demonstration in a relevant environment)) are summarized in a comprehensive table. Some examples on sensor requirements and the possible timetable for implementing advanced technologies for the various sensing variables are discussed in the following.

For temperature sensors approaching 1700°C operational environment SiC and SiCN technologies are considered to have the highest potential. Various other techniques are being explored, but may not provide the required performance at high temperatures. The TDL technique has been demonstrated on full-scale gas-turbine combustor sector test stands, but challenges have to be addresses before implementation can be considered.

Pressure sensors that operate in an environment with temperatures below 250°C are largely available. Pressure sensors capable to operate in environment with temperatures from 250°C to 750°C are commercially available, however these sensors are used mostly on the test stands or for "rumble" or "screech" monitoring of GTE with augmentor, because they cannot measure static pressure and aerospace GTE, compared with industrial aeroderivative GTE, does not allow yet for controlling fuel delivery to each individual fuel nozzle. Pressure sensors that have to operate in temperature environment exceeding 750°C are not existent and are foreseen to be based on SiC and SiCN. Smart sensors based on SiC technologies are foreseen to be largely available by 2015. SiCN technology for pressure sensors and integrated electronics is not foreseen to be available earlier than 2020. Both SiC and SiCN technologies come with a great potential however, because of potentially embedding such high temperature sensors within the structure.

Vibration sensors located remotely from the fan and turbine could face significantly high temperatures (up to 750°C); therefore standard MEMS piezoelectric accelerometers cannot be used. Extension of the MEMS principles from Si or piezoelectric technology to SiC and SiCN technologies might significantly extend the capability of such systems to operate at high temperatures. The timeline for SiC and SiCN technologies applied to micro-accelerometers follows the same time frame as presented above. Non-contact sensing based on Doppler Velocity Interferometer is available for measurements at a temperature range from –65°C to + 125°C.

Emission species and exhaust gas composition sensors are largely available for test rig measurements. Sensors based on spectroscopy are far from a commercial product. TDL technology appears to be the most promising technology. However, challenges include "optical engineering" (dealing with heat transfer effects on fibers and windows and developing robust hardware designs for these components, and also for lasers, electronics and data processing) and "optical science" (optimizing the selection of wavelengths and sensing strategy). Spectroscopy technology is currently at TRL 2 and could be at TRL 6 in 2020.

Tip clearance and position/arrival time sensors have been demonstrated using capacitive sensors (now at TRL1 and TRL 6 expected in 2020) and microwave sensors (now at TRL 5 and TRL 6 in 2010). These sensors can operate at temperatures as high as 600°C. For higher temperature ranges up to 1700°C, SiCN based sensors are required; the timeline for the development for such sensors is 2020 or later.

Torque sensors to evaluate the real-time trust of the engine are largely available and are implemented in few classes of engines (helicopter turbine engines). Such sensors are in an advanced development state and implementation is expected within the next three years. The existent technology needs to be integrated in specific designs, the size of the sensors has to be reduced, reliability has to be improved, and drift from the calibrated point has to be minimized. The timeline for such type of sensors is 2010.

The need for sensors for determining air mass flow (without interference with flow), fuel mass flow (for high temperature operation at burners' nozzles), and fuel properties (on-board during or after re-fueling) has been identified for thrust and energy estimations. No sensors are available. The challenges to accomplish such type of sensors are significant, and it estimated that they are not available before 2020.

Chapter 7 outlines *Actuator Requirements and Roadmaps*. Generic **actuator** requirements for three common actuation functions were addressed, including:

1) Flow manipulation (of the boundary layer by either mechanical effects or aerodynamic means with blowing or sucking air);

2) Large scale flow switching (valves with applications to stall/surge control, bleed flows, cooling flows, other); and

3) Mechanical manipulation (intakes, variable guide vanes and nozzles).

Generic requirements for these three common functions have been summarized in terms of operational environment and performance/capabilities depending on component applications. In addition generic actuator requirements for fuel flow control, geometry control, and requirements for specific compressor/turbine applications (tip clearance and vibration) were added. Although generic requirements can be identified, developments towards these environmental requirements must be intimately coupled to the specific application requirements in order to satisfy the overall constraints.

Current actuation within a gas turbine has largely been limited to the five main variables, namely fuel input, variable guide vanes, bleed valves and variable geometry intakes and nozzles. First generation tip clearance control using casing temperature has also recently been added. Specific capabilities for various components were described.

Actuation within a gas turbine requires consideration of the interaction with the engine cycle. For example effects on air flows, combustion temperatures, etc., must consider integration into the engine components. Technology evaluation has to identify the current capabilities and likely future developments including full system requirements, costs, maintenance, failure modes, etc.

Established actuators such as hydraulics, electrical and even fluidics still offer considerable opportunities for future developments. Emerging technologies include:

1) Electroactive materials, including piezoelectric ceramics and Electro Active Polymers (EAPs);

2) Shape memory materials;

3) Magnetic strained materials (providing magnetostrictive effects);

4) Magnetic Shape Memory (MSM) or Ferromagnetic Shape Memory (FSM) materials; and

5) Microsystems, micromachines and MEMS.

Approaches of extending standard technologies and applying new technologies are discussed for the various components.

Actuator applications to the various components together with specifications, candidate technologies, current TRL, time to achieve TRL 6, and the challenges have been summarized in a comprehensive table. Current actuator TRL levels of 2 (for electro-magnetic and hydraulic actuation and high-temperature shape memory alloys both for tip clearance control) to 5 (for pneumatic actuation for tip clearance control) have been identified. The majority of the actuator technologies are considered currently at TRL 3. The years to achieve TRL level 6 range from 2010 (for electro-magnetic, miniaturized valves for fuel flow control and large-scale flow switching for compressor stator vanes and pneumatic tip clearance control) to 2020 (for high temperature shape alloys for turbine tip clearance control). Devices for micro-scale flow manipulation are considered to be at TRL 6 in between 2013 and 2018 mainly depending on operational temperatures and for geometric control in 2012 (standard action principles) to 2018 (shape memory alloys).

8.2 ROADMAP

The benefits of enabling technologies for the "More Intelligent Gas Turbine Engines" in terms of improved Performance, Safety, Affordability and Reliability, and reduced Environmental Impact are summarized in Table 8.1. These benefits are listed as High (H), Medium (M), and Low (L) to provide a qualitative assessment, and are summarized by the technologies discussed in the three main areas: Actively Controlled Components; Intelligent Control and Health Monitoring; and Distributed Engine Control. The anticipated timeframe for the technologies to reach TRL 6 is also provided along with some notes to give additional information such as the actuation/sensing technologies required to reach TRL 6.

Table 8.1: Component Roadmaps

Applications	Technology Areas	Year to Achieve TRL 6 Goal			Benefits (H, M, L)					Notes
		2010	2015	2020	Performance	Safety	Affordability	Reliability	Environmental Impact	
Actively Controlled Components	Inlet									
	Active inlet control		x		H					Inlet geometry control for supersonic speed
	Active inlet flow control		x		M	M				Pulsed microjets
	Active noise control		x		L				H	Fan noise control; pulsed microjets
	Compressor (AC of)									
	Surge	x			H					Using pulsating jets
	Flow			x	M					Pulsed microjets; elevated temperature
	Clearance		x		H					Pneumatic actuation
	Vibration		x					H		Piezo-electric actuation
	Combustor (AC of)									
	Combustion instability	x			H					Pulsed fuel injection; electro-magnetic valves
			x							Magneto-strictive
	Emission		x						H	Magneto-strictive
	Pattern factor	x			H					Electro-magnetic
	Turbine (AC of)									
	Clearance	x			H					Pneumatic actuation
				x						SMA
	Cooling air				H					Flow control valve at elevated temperature
	Nozzle									
	AC of noise			x					H	SMA actuation at elevated temperatures
	Thrust vectoring			x	H					Flow control valve for cross injection
Intelligent Control and Health Monitoring	Model based control		x		H	H				Current sensors with enhanced capabilities; SiC sensors
				x						New types of sensors with SiCN and TDL technologies
	On-board condition monitoring		x		H	H		H		Current sensors with enhanced capabilities; SiC sensors
				x						New types of sensors with SiCN and TDL technologies
	Adaptive control		x		H	H				Current sensors with enhanced capabilities; SiC sensors
										New types of sensors with SiCN and TDL technologies
Distributed Engine Control	Partially decentralized control		x		L			M		Component level control implemented locally and integrated with FADEC
	Fully distributed control			x	L			M		Performance - although low direct performance improvement, . .
										this is critical for improved capability in terms of
										enabling active component control
										Affordability - improvement is in reduced operational costs
										through better diagnostics and "easier" upgrade capability

8.3   RECOMMENDATIONS

The concept of more intelligent gas turbine engines should be approached by incremental changes, both by improving existing technology and components and implementing new technologies. Although numerous newly built propulsion systems are already using intelligent components, it is expected that a sustained effort in the implementation of the distributed active control will be attempted, once the technologies targeted in this report are developed and demonstrated. A close interaction between the "Customers" and "Researchers" and "Technology Developers" is needed to optimize investment for meeting challenging for performance and implementation-related requirements. Recommendations for sensors and actuators activities are summarized in the following to achieve a goal of TRL 6 (fully demonstrate engineering feasibility) in the near-term (3-5 years), mid-term (7 to 10 years), and long-term (12 to 15 years).

8.3.1 Sensors

8.3.1.1 Near-Term Goals (about 2012)

For sensors, which are available now or have proven concepts (TRL 3), work should focus on prototyping and implementation for the target environment and interfaces. Examples are sensors for tip clearance (microwave sensing), position and arrival, and torque. Also sensing capability for health monitoring should be improved by adding vibration sensors for the fan and adding conventional gas path pressure and temperature measurements at locations that are presently not instrumented due to the harsh environments, including high temperatures.

Implementation of pressure sensors to determine inlet distortion and stall margin should be considered. The need for non-interference with the flow and exposure to ice, rain, sand, and dust has to be addressed.

Insertion of sensors for turbine emission species and exhaust gas composition should be considered. Such sensors are now available for low temperature operation. Improvements in the performance of electronic noses through nanotechnologies should be further pursued.

8.3.1.2 Mid-Term Goals (about 2016)

SiC (Silicon Carbide) technology should be further explored and transitioned, as soon as possible, to technical feasibility demonstrations. This includes technologies for specific sensor types and entire electronic circuits, which would allow development of smart sensors.

Sensors based on spectroscopy should be further explored. Tunable Diode Laser (TDL) technology appears to be the most promising technology. Challenges dealing with heat transfer effects on fibers and windows, robust hardware designs, and optimization of sensing strategy should be addressed.

8.3.1.3 Long-Term Goals (beyond 2020)

SiCN (Silicon Carbide Nitride) technology should be further explored and proof of concept validation should be provided, both for specific sensors and integrated electronics.

Other promising technologies should be pursued, including embedding of high temperature SiC and SiCN sensors, the application of spectroscopy, and advanced sensing principles for sensors (for example capacitive sensing for tip clearance).

In addition basic research should be initiated to identify sensing principles and define concepts for sensors to determine mass flows and fuel energy properties for thrust estimation.

8.3.2 Actuators

8.3.2.1 Near-Term Goals (about 2012)

Established actuator principles such as hydraulics, electrical and fluidics should be further considered to address future actuator requirements. New opportunities to develop higher temperature and miniaturization capabilities should be pursued, while considering full system requirements, costs, maintenance, failure modes, etc.

Prototyping of several actuators now at TRL3 should be considered. These include micro-jets and micro-flaps for inlet flow control, low-temperature piezo-electric and electromagnetic devices for geometry control (inlet),

electro-magnetic valves for large-scale flow switching for compressor stator vanes, electro-magnetic and magneto-strictive valves for fuel flow control, and pneumatic and electromagnetic actuators for tip clearance control.

8.3.2.2   Mid-Term Goals (2016)

Work should address micro-jets with increased mass flow and higher temperature capabilities and flow control valves with further increased flow capabilities. Applications for low-temperature SMA (Shape Memory Alloy) for geometric control should be considered, as well as hydraulic and piezo-electric actuators for tip clearance control. High-temperature applications of the piezo-electric, hydraulic, and electro-magnetic actuation principles should be explored.

8.3.2.3   Long-Term Goals (beyond 2020)

High-temperature applications for SMA and electromagnetic principle should be addressed (for example for tip clearance control). Also other emerging technologies such as Electro Active Polymers (EAPs) and Magnetic Shape Memory (MSM) or Ferromagnetic Shape Memory (FSM) materials should be explored for potential actuators.

8.3.3   Other Technologies

In addition to addressing sensor and actuator needs the following technologies should be addressed: power supply for distributed on-board electronics, Wi-Fi transmission with 99.999% fidelity, energy harvesting for sensors, and spintronics as novel sensing principle.

8.3.4   Follow-on Activity

It is recommended that the AVT Panel establish a new Task Group to demonstrate feasibility and reliability of new technologies in sensors and actuators [8.1]. The approach will be that the researchers will provide sensor and actuator prototypes along with the expected specifications to the sensor and actuator manufacturers, who will package and prepare the devices for the testing. The units will be shared by propulsion systems manufactures and incorporated in the engine tests to determine achievable specifications.

8.4   REFERENCE

[8.1]   Appendix 7 – TAP for Proposed Task Group for Demonstration of Advanced Sensors and Actuators Capabilities for Future Propulsion Systems.

TR-AVT-128 APPENDICES

Appendix 1 – RTB Endorsed Proposed NATO Hardware TRL Definitions (24 September 2007)

View Appendix 1

Appendix 2 – AVT-128 Task Group Participants

View Appendix 2

Appendix 3 – Technical Activity Proposal (TAP) for AVT-128

View Appendix 3

Appendix 4 – Terms of Reference (TOR) for AVT-128

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Appendix 5 – Task Group Meetings (Dates and Places)

View Appendix 5

Appendix 6 – Roadmap for MEMS Application to GTE Active Control (TR-AVT-078)

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Appendix 7 – TAP for Proposed Task Group for Demonstration of Advanced Sensors and Actuators Capabilities for Future Propulsion Systems

View Appendix 7

Annex A – RTO SYMPOSIUM PRESENTATIONS

Annex A.1 − R.K. Hanson, J.B. Jeffries, and M. Allen, *"Tunable Diode Laser Absorption Sensors for Aeropropulsion Testing",* Applied Vehicle Technology Panel Specialists' Meeting on Recent Developments in Non-Intrusive Measurement Technology for Military Model and Full-Scale Vehicles, April 2005, Budapest, Hungary.

   View Presentation   View Report

Annex B – TASK GROUP PRESENTATIONS

Annex B1.1 – Dave Kenison, *"Intelligent Propulsion System: An Engine Manufacturer's Perspective"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE

View Presentation

Annex B1.2 – Sanjay Garg, *"Controls and Health Management Technologies for Intelligent Aerospace Propulsion Systems"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE

View Presentation

Annex B1.3 – Frank Grauer and Hugo Pfoertner, *"Micro System Technology in Future Engine Applications – Objectives and Next Steps"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE

View Presentation

Annex B1.4 – Sven-J. Hiller, *"New Flow Actuation Concepts to be Studied Within European Technology Program ADVACT"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE

View Presentation

Annex B1.5 – Ion Stiharu, *"Pressure Detection in GTE"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE

View Presentation

Annex B1.6 – Pavol Rybarik, *"Vibro-Meter"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE

View Presentation

Annex B1.7 – T. Walter, D. Haeringer and J. Goschnick, *"Gas Analytical Gradient Microarrays for Chemical Condition Monitoring in Intelligent Systems"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE

View Presentation

Annex B1.8 – Muthukumaran Packirisamy, *"Detection of Physical Quantities and Optical Measurements in GTE"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE

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Annex B2.1 – Dave Kenison, *"Intelligent Propulsion System: Key Enablers"*, AVT Task Group 128 Meeting, April 05, Budapest, HUN

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Annex B2.2 – Taylor Rosenfeld, *"GE Transportation Perspective – Intelligent Engine Technologies"*, AVT Task Group 128 Meeting, April 05, Budapest, HUN

View Presentation

Annex B2.3 – Frank Grauer, Eckart Henrich, Sven Hiller, *"Advanced Compressor Design Using Micro System Technology"*, AVT Task Group 128 Meeting, April 05, Budapest, HUN

View Presentation

Annex B2.4 – Patrik Hendricks, *"Intelligent Gas Turbine Engines Adaptive Engine Control – Some Ideas"*, AVT Task Group 128 Meeting, April 05, Budapest, HUN

View Presentation

Annex B2.5 – Klaus Schadow, *"Active Combustion Control – Review of Recent Selected Activities"*, AVT Task Group 128 Meeting, April 05, Budapest, HUN

View Presentation

Annex B3.1 – Mehran Mehregany and Srihari Rajgopal, *"Examples of SiC Sensor R&D Activities"*, AVT Task Group 128 Meeting, October 2005, Granada, ESP

View Presentation

Annex B3.2 – Mehran Mehregany and Li Chen, *"A High-Temperature SiC Pressure Sensor for Propulsion and Power Generation Applications"*, AVT Task Group 128 Meeting, October 2005, Granada, ESP

View Presentation

Annex B3.3 – Mehran Mehregany and Xiao-an Fu, *"SiC Sensor Interface Electronics"*, AVT Task Group 128 Meeting, October 2005, Granada, ESP

View Presentation

Annex B3.4 – Mehran Mehregany and Ravi Burla, *"Nickel Wire Bonding for High-Temperature Packaging of Sic Devices"*, AVT Task Group 128 Meeting, October 2005, Granada, ESP

View Presentation

Annex B3.5 – David Shephard and Barbara Wright, *"Engine Health Diagnostics using Radar"*, AVT Task Group 128 Meeting, October 2005, Granada, ESP

View Presentation

Annex B3.6 – Rolls-Royce, *"Intelligent Engine and Integrated Power System"*, AVT Task Group 128 Meeting, October 2005, Granada, ESP

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Annex C – REPORTS

Annex C.1 – Donald Simon, *"Sensor Needs for Control and Health Management of Intelligent Aircraft Engines"*, NASA TM-2004-213202

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Annex C.2 – S. Garg, *"Controls and Health Monitoring Technologies for Intelligent Propulsion Systems"*, NASA TM-2004-212915

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Annex C.3 – J.S. Litt, et al., *"A Survey of Intelligent Control and Health Monitoring Technologies for Aircraft Propulsion Systems"*, NASA TM-2005-213622

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Annex C.5 – D.E. Culley, R. Thomas, and J. Saus, *"Concepts for Distributed Engine Control"*, NASA TM-2007-214994

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14. Abstract

Increased emphasis on aircraft safety, enhanced performance and affordability, and the need to reduce the environmental impact of aircrafts are being addressed through the concept of Intelligent Propulsion Systems. These systems are potentially enabled through increased efficiencies of components through active control, advanced diagnostics and prognostics integrated with intelligent engine control, and distributed control with smart sensors and actuators. The focus of this report is on "On-Board Intelligence", and the discussions are limited to the overall engine gas-path performance perspective. The emphasis throughout the report is on identifying the sensor and actuator needs to realize these intelligent engine concepts and identifying the current sensor and actuator technologies and roadmaps for emerging technologies. The report is of interest both to the "Customers" to understand the investment needs and the "Researchers" and "Technology Developers" to understand the technology needs for closing the gap from current sensor and actuator capabilities to future performance and universal requirements and targets.

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