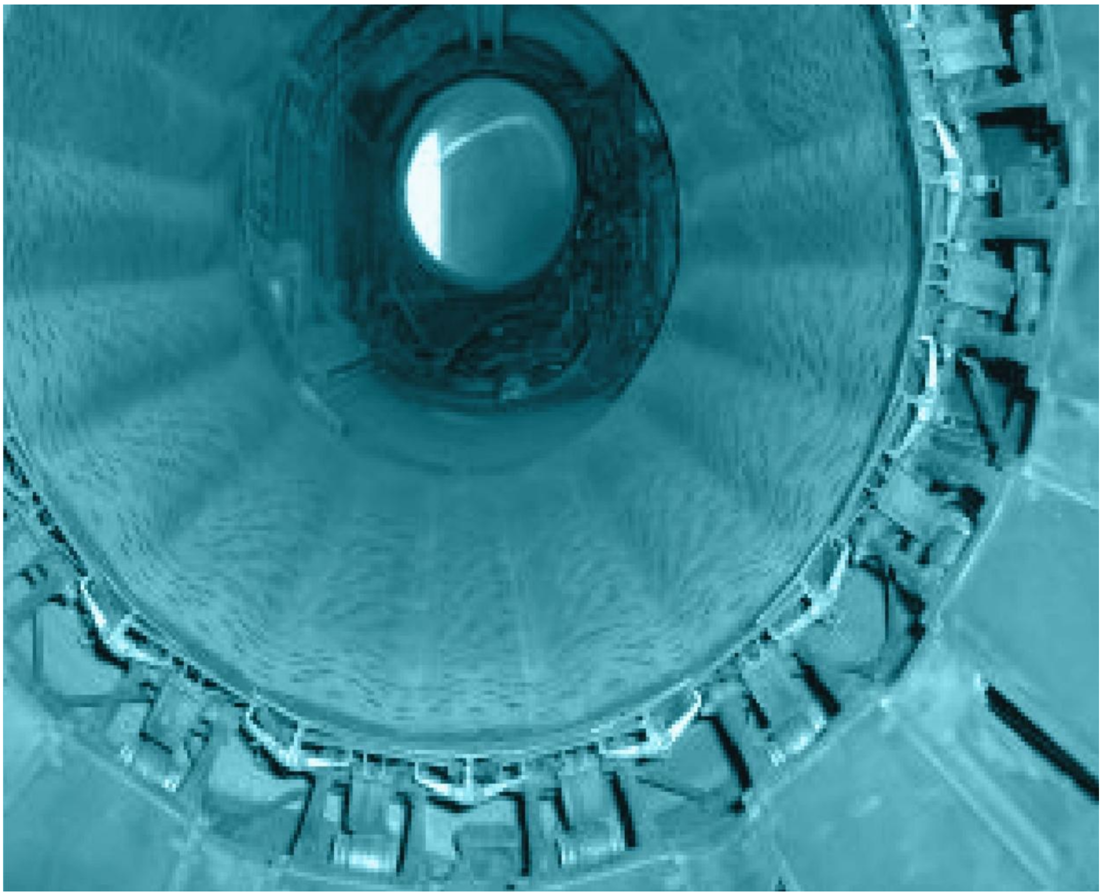
Strategies for a Cleaner Exhaust

Main Thematic Area: Aircraft Operations



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Contents

Acronyms and Abbreviations Used

ACC	Active Clearance Control
CO	Carbon Monoxide
DECS	Digital Engine Control System
EEL	Extended Engine Life
EGT	Exhaust Gas Temperature
EPR	Engine Pressure Ratio
GTE	Gas Turbine Engine
HBV	Handling Bleed Valve
HUMS	Health and Usage Monitoring Systems
LCF	Low Cycle Fatigue
LECS	Life Extending Control System
LLP	Life Limited Parts
MAFC	Micro Adaptive Flow Control
MEMS	Micro Electrical Mechanical Systems
NH	Rotational speed of 2^{nd} spool
NH_{dot}	Rate of Change in speed of 2^{nd} spool
NO_X	Nitrous Oxides
OEM	Original Equipment Manufacturer
ppm	Parts per Million
SFC	Specific Fuel Consumption
TGT	Turbine Gas Temperature
UHC	Unburnt Hydrocarbons
VSV	Variable Stator Vane
W	Total Engine Airflow

1.0 Introduction

As part of OMEGA's objective to investigate the environmental effects of the air transport industry, this project is devoted to the study of control strategies for a cleaner exhaust. Environmental concerns and legislative deadlines have prompted renewed research in developing more clean technologies for gas turbine engines. The scope of the research ranges over the development and adoption of new materials and manufacturing processes through to new combustion methods and advanced control laws for the engine.

In the first report [8], the effect of changing the position of the inlet guide vanes in terms of fuel consumption and ultimately emission from the Gas Turbine Engine (GTE) was discussed.

This report discusses the life enhancing control strategies that are being considered for improving GTE life while not affecting performance. Engine life improvement may be in terms of lower servicing times and reduced maintenance effort. Also, the enhancement schemes should, if possible, decrease the emissions from the engine. Lower emissions rates call for an optimum consumption of fuel; operating costs can be affected by fluctuations in the cost of aviation fuel in the global market. Also extended on-wing life and engine serviceability is important to manufacturers and customers and so a compromise has to be found between these two objectives.

Technology road maps currently available for extending the life of a GTE are reviewed in brief in Section 2. This section also introduces techniques such as wavelet transforms, neural networks, etc which are used for prognostics and signal processing. Seven different life enhancing control strategies on GTE are discussed in Section 3 with their potential advantages and disadvantages. This section discusses existing control strategies and also proposes new control strategies for enhancing engine life. Section 4 concludes and summarises the work.

2.0 GTE Life Extending Technology Overview

From both an economic and an operational viewpoint, it is clearly desirable to obtain the maximum amount of useful life from the components of a GTE, as this reduces the maintenance costs of the engine and increases aircraft availability. While OEMs are constantly refining their designs to handle higher temperatures and stress levels, these improvements often do not translate into an equivalent increase in component life due to the ever-increasing performance requirements of modern aircraft. Aircraft, through a much broader range of manoeuvres during flight, require engines to go through more transient operations than before. Experience has shown that transient operations are more detrimental to the life of gas turbine engine components than an equivalent amount of time spent at continuous full power operation.

In the past, component lifetime calculations were usually based on empirical relations derived from experimental data. More recently, manufacturers have begun to develop Health and Usage Monitoring Systems (HUMS) [11] to include limited information on the actual operating conditions of the engine, as recorded by on-board sensors, in the remaining life calculations. While this is an improvement over earlier methods, it still does not fully utilise the enormous amount of sensor data available in current engines and these life monitoring systems take a passive role in the life extension process. That is, they provide the user with more accurate information on the remaining useful life of a component, thus allowing the user to safely extend the component's service life before its replacement, but the systems do nothing to actively reduce the rate of damage accumulation in an engine component [4].

After a fixed number of operation cycles of a GTE (which varies from manufacturer to manufacturer) engine components are replaced or need to be replaced. Mechanical systems design and development has been continually refined to make these components last longer and satisfy requirements. The trend is now towards the increasing use of composite materials in fabrication to reduce weight and augment fuel efficiency. During the course of service, virtually all composite structures should be monitored to ensure their condition of health and integrity to prolong their life span or prevent catastrophic failure.

Recent developments in sensor and actuator technologies have opened the way to develop new diagnostic technologies, particularly suitable for composite materials. Such enhancements might involve approaches such as wavelet transforms, neural networks, fuzzy logic, probabilistic estimators, system identification, electro-mechanical impedance methods, electric impedance tomography, etc. A brief description of some the more popular techniques follows:

- Wavelet Transforms:
  Wavelets are mathematical functions that cut up data into different frequency components, and then study each component with a resolution matched to its scale. They have advantages over traditional Fourier methods in analyzing physical situations where the signal contains discontinuities and sharp spikes. Wavelets have applications in areas of image compression, turbulence, human vision, radar, and earthquake prediction, generating musical tones and de-noising data.

  These algorithms are used in GTEs to give a view of the Prognostic Health of the system. The approach has been guided by the principle of maximising the value of existing sensor sets. The core idea explored is the value in moving beyond time-based analysis of the low frequency signal, to an analysis of the full bandwidth of the existing sensor measurements. Acquired data from the sensors on the

GTE is processed using time-frequency domain techniques of the wavelets, which allows the analysis of high frequency phenomena. Wavelet transforms provide an efficient and elegant solution to the creation of a time-frequency representation of the signals, and these have been used to develop prognostic feature detectors as well as system identification with improved noise handling capability.

- Neural Networks:
  Neural networks attempt to mimic the operation of a human brain works, based on a network of simulated biological neurons. Artificial neural networks are effective as pattern recognition engines, exploiting the model of parallel distributed processing offered by the human brain.

  The artificial neuron is a mathematical model of the neuron which approximates the actual working of the neuron (Figure 1). It has a non-linear function which acts as the decision centre connected to a number of inputs and outputs.

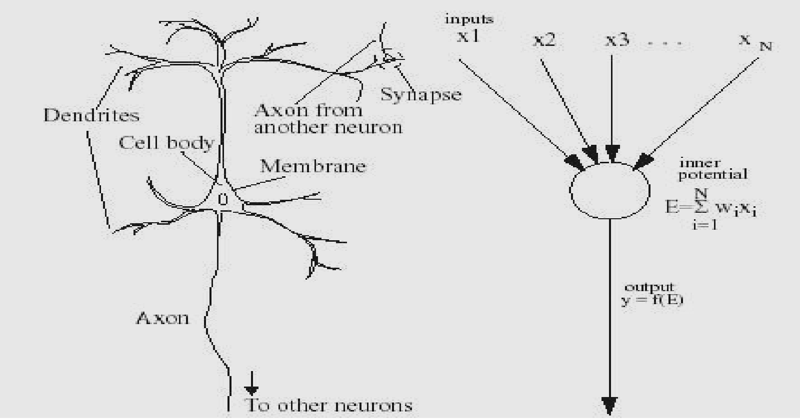


Figure 1: Biological & Artificial Neuron [12]

The neuron is connected to other layers of individual neurons to form an Artificial Neural Network (ANN) as seen in Figure 2.

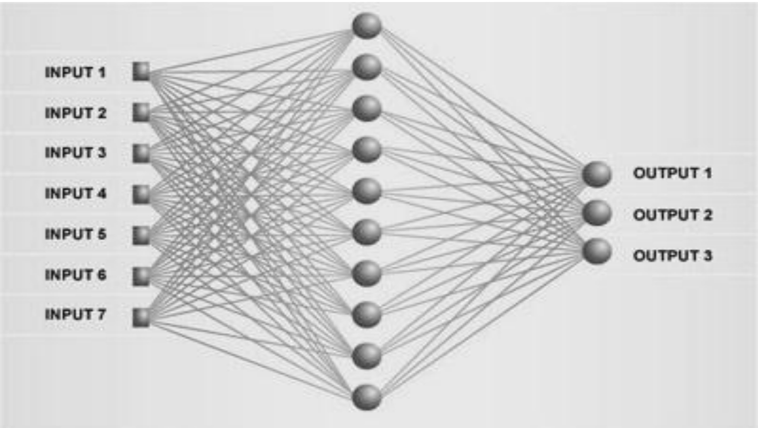
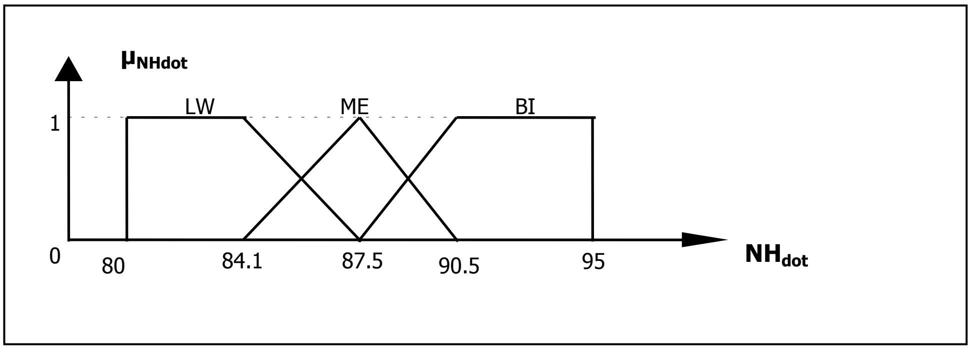


Figure 2: Typical ANN[10]

The network has an input layer, a hidden layer and an output layer, each layer consisting of many neurons, all connected. These networks are trained using different techniques. In supervised learning, a set of example pairs like $(x, y), x \in X, y \in Y$ are provided and the objective is to find a function f in the allowed class of functions that matches the examples so as to infer how the mapping implied by the data and the cost function is related to the mismatch between the mapping and the actual data. In unsupervised learning, a cost function, relevant to the problem, is defined in terms of x and f. For a given set of data x, this cost function is minimised and the network attempts to find the best solution. Application areas of neural networks which are significant for use in GTEs are controller tuning, signal processing and fault recognition.

- Fuzzy Logic:
  Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory which deals with reasoning that is approximate rather than precise. Just as in fuzzy set theory, where set membership values can range inclusively between 0 and 1, in fuzzy logic the degree of truth of a statement can range between 0 and 1 and is not constrained to the two absolute values of true, and false. This is conceptually different from probabilistic theory which defines the likelihood of some event or condition, instead fuzzy logic represents membership of a group as true or false. This membership concept is used to define a variable's operational profile, called the truth map. The truth map then defines a membership function μ. For a 2-spool GTE, for example, fuzzy logic can be used to define membership functions for the 2nd spool speed (NH), the change in NH (NH_{dot}) & fuel flow (WFE) as shown in Figure 3 for defining a WFE controller [3].



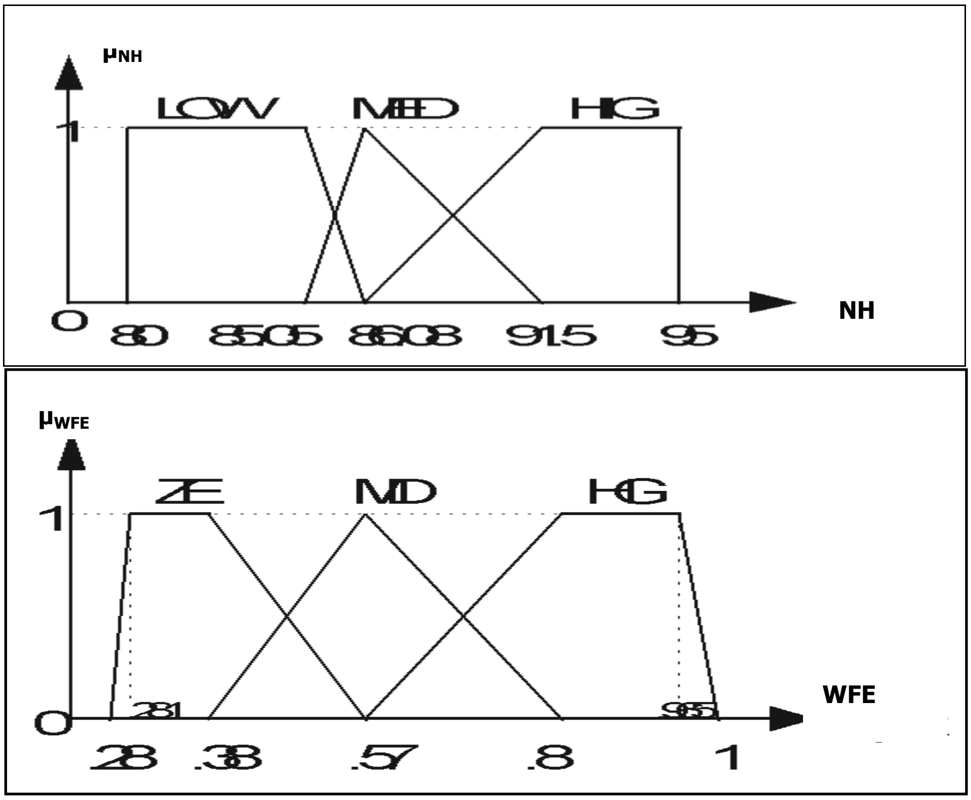


Figure 3: Membership Functions for NH, NH_{dot} & WFE [3]

These membership functions then can be used to define a rule base for a WFE controller shown in Table 1, where, for example,
If NH is low & NH_{dot} is low, then the controller WFE has the value of zero.

NH_{dot} / NH	LW	ME	BI
LOW	ZE	ZE	MD
MED	MD	MD	MD
HIG	MD	HG	HG

Table 1: Rule base of WFE Controller [3]
(ZE= zero, MD=medium, HG=high, LW=low, ME=medium, BI=big)

These techniques are used as signal processing tools to extract relevant engine data from the ambient noise so as to form a database of the different parameters of the engine as well as checking on the prognostic health of the system. The database can be used for analysis of the health status of the engine in order to take corrective actions and/or schedule maintenance of the engine accordingly. Associated software will take account of the presence of distributed sensors, actuators, and controllers based on fibre optics, piezoelectric materials, MEMS devices, or other concepts.

The development of new active materials, such as relaxor ferroelectrics and alkaline-based piezoelectric materials has recently been reported by the materials science research community. A relaxor ferroelectric is a type of smart material in which one or more properties can be significantly changed in presence of external stimuli like stress, magnetic and electric fields. These materials have high relative permittivities and extraordinarily high electrostrictive coefficients. These materials possess high mechanical strength, high dielectric strength and excellent machinability characteristics [6]. These materials may offer significant opportunities to create improved actuation devices that will deliver greater authority (force, stroke) than do the conventional piezoelectric materials [1]. Use of smart structures indicates a possibility of obtaining enhanced operability and hence operating profit in simulation studies [1].

Next-generation research has been focused across the globe on developing control systems that enhance on-wing engine life. Various technological challenges and novel concepts are being proposed. Also, interestingly, there is a demand on lower emissions due to stringent legislations and there has been a relationship between better emission control and engine life.

3.0 Life Enhancing Control Strategies

Some engine life enhancing concepts are discussed in this section. The emphasis is on enhancing engine line by developing suitable control schemes.

3.1 Health and Usage Monitoring Systems (HUMS)

Systems like HUMS are used to monitor the health of the engine but are passive in nature as far as extending the life of an engine is concerned. Caplin and Ray [4] claim that, by using sensor data available to the OEMs, a control system can be designed to extend the service life of components of the engine before replacement. For this, simple structural and damage models of critical engine components are developed. These models are proposed to be used offline to assess the current damage state of the engine based on the data obtained from the sensors. These damaged models are then incorporated into an overall plant simulation to synthesize a control law called LECS that seeks to minimise damage accumulation with minimal system degradation. The closed-loop control scheme is shown below in Figure 4.

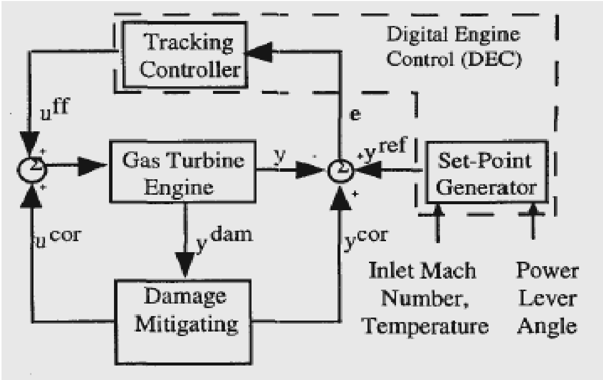


Figure 4: Control schematic using critical models [4]

LECS is intended to augment the existing Digital Engine Control System (DECS) of the engine, rather than replacing it. Under normal operating conditions, the DECS has full control authority, while the LECS simply monitors the damage state. When the LECS determines that after use for a certain time, the engine becomes particularly vulnerable to damage at its current operating condition; the LECS is activated and provides fast corrective action to prevent an unacceptable amount of damage accumulation. When necessary, the LECS acts to temporarily alter the set-point, thereby preventing the DECS from nullifying its control actions as, under normal conditions, if LECS tried to modify the control action directly, DECS would interpret it as a disturbance and nullify its effects. This implies that both the control schemes would compete with each other to gain control under normal conditions and this is not intended. LECS is not allowed to have control at all times as damage dynamics are slower than system dynamics and is activated only when conditions indicate damage accumulation. Robust control design techniques, such as μ-synthesis, can be used to develop LECS, although the tuning of LECS is subject to further research [4].

3.2 Adaptive-Predictive Control System

Another approach is to develop a dynamic gain scheduled adaptive-predictive control system for extending engine life. Predictive control can be compared with driving a car, looking forward and slowing the car when, say, there is a pedestrian crossing ahead; that is, predictive control looks into the future, anticipates future events and takes corrective action at the present instant. Adaptive control enables the control to change and adapt as the engine hardware degrades over time. During the operation of the engine, the sensor data obtained for HUMS can be used to interpret possible engine degradation by comparing with the original plant data. This information can then be used to enable the adaptive models to change the model parameters as the engine degrades while the predictive controller then computes the control moves based on the new model so as to minimise the change in performance with the degraded engine life. One of the advantages of using predictive control is the ability to predict the start of engine degradation and take immediate corrective action in the present instant so as to enhance engine life while not sacrificing performance. Each degradation condition then will effectively have its own model and there will be a bumpless transfer among them. "Bumpless transfer" entails switching between the models is such a way that the output follows a smooth transition to its new value. The concept schematic is shown in Figure 5.

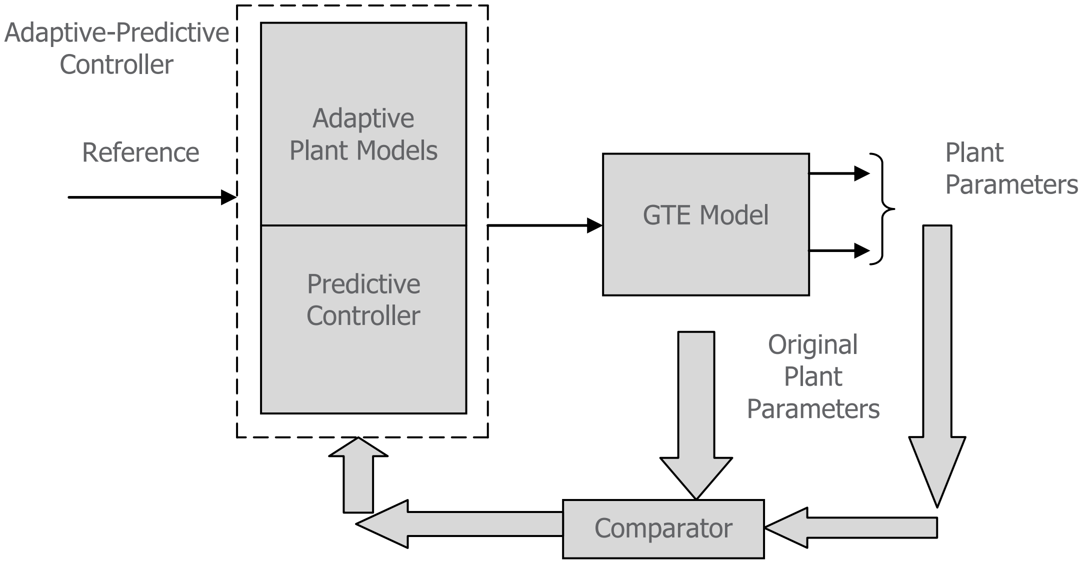


Figure 5: Adaptive-Predictive Control Scheme

3.3 Micro Adaptive Flow Control (MAFC) System

Another GTE life-enhancing control strategy is the use of MAFC systems. OEMs are working on this technology already. MAFC technologies enable control of large-scale aerodynamic flows using small-scale actuators. MAFC technologies combine adaptive control strategies with advanced actuator concepts such as micro-scale synthetic jets: Micro Electrical Mechanical Systems (MEMS)-based micro-actuators, pulsed-blowing actuators, plasma actuators, and combustion actuators to control the aerodynamic flow by injecting perturbations periodically [7, 8]. They have been implemented on the wings of test aircraft [7] and it has been reported that using MAFC in an aircraft increases aircraft payload from 9% to 14%.

Wherever there is a separated flow of a fluid, MAFC can potentially reduce the separation and lower the energy loss in the system [7]. This would, in turn, increase maximum lift and reduce drag on the rotors, compressors etc. Some potential benefits could be [8]:

- To cause the delay, or prevention, of fluid flow separation;
- To induce flow separation in previously unseparated flow;

- To alter supersonic flow shock structure; or
- To otherwise alter the large-scale flow field and provide overall system benefit in terms of engine life extension.

The MAFC concept can also be extended on gas turbines to potentially enable better surge margin regulation. The idea will be to keep the working line at a predefined distance from the surge line in as in Figure 6 in order to avoid surge especially during transient operation of the engine. Use of MAFC could further optimise the working line position.

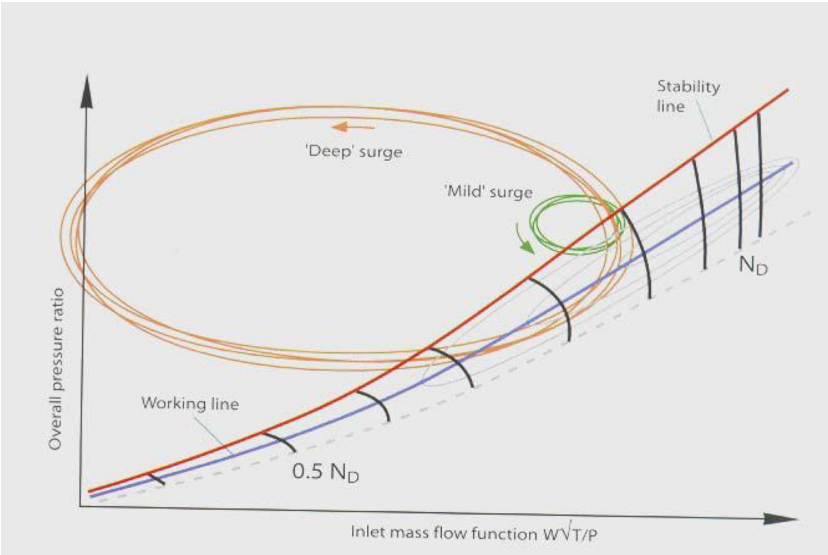


Figure 6: Surge cycles of Compressor [14]

MAFC Systems can also be used in the combustor to control flow separation in the combustion chamber (Figure 7) with the objective of obtaining optimum combustion characteristic so as to enhance component life down stream. Technological challenges also remain in making MAFC system rugged and affordable [7].

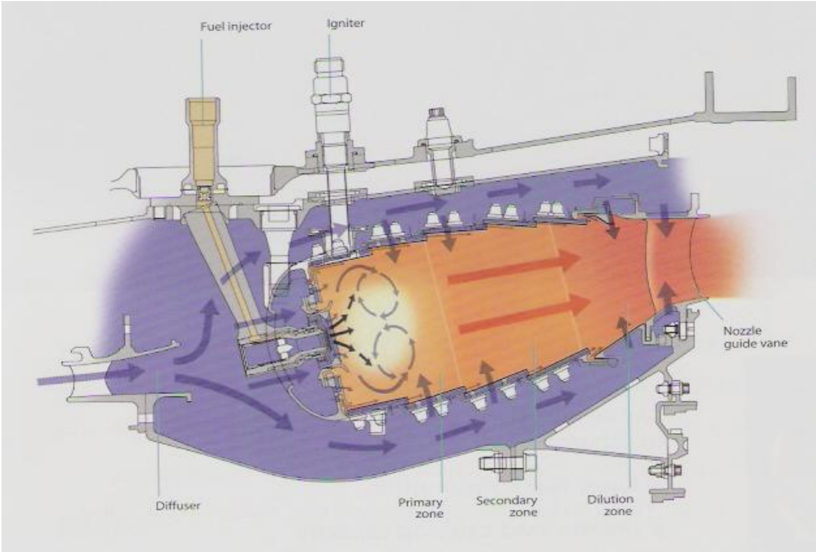


Figure 7: Combustor Chamber [14]

3.4 GTE Life Enhancing System

Although the components of the engine are replaced after the end of their useful life, their lifetimes are not measured in terms of their structural viability alone. There are other factors that determine their replacement even when they are structurally sound and could remain in service. One example could be that of replacing certain components which may have been exposed to high temperatures for a certain amount of time, although these components may not be necessarily faulty. If an engine has slow acceleration, overhauling of the engine is normally carried out which causes sometimes structurally sound components to be discarded.

A control scheme proposed by Sridhar [16] addresses the issue of increasing the lifetime of such components. The first part deals with the issue of engine acceleration. The delivery of fuel to the engine is normally scheduled in the controller, with fine tuning from the VSVs. If an acceleration demand for an engine fails to meet the target, instead of going for overhaul, the proposed control system:

- increases the fuel schedule, and
- increases the compressor stall margin.

This causes the acceleration to reach the target. To achieve this, it is first determined whether the acceleration has fallen below the target by giving a take-off acceleration demand to the engine. The demand acceleration generated by the engine is measured and compared with the required acceleration. If it falls below the target, the controller adjusts the fuel schedule by increasing the fuel flow by 5%. Increasing the fuel flow decreases the stall margin of the compressor. The controller counteracts this by increasing the compressor bleed thereby increasing the stall margin. When the full acceleration target is reached is reached, the bleeds are terminated. This is illustrated in Figure 8. Increase in fuel flow increases the operating costs. However, when there is a fluctuation in fuel prices, a satisfactory compromise must be made between operating costs and on-wing life/serviceability issues.

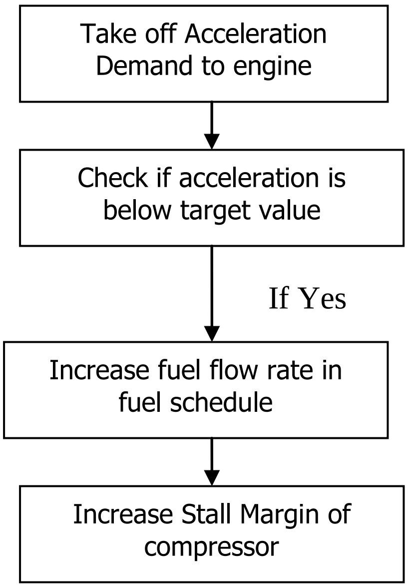


Figure 8: Flow chart for increasing fuel flow rate by the life enhancing system [16]

In another part of this system, the system increases the cooling on certain components when they reach the end of their thermal cycle limit. A thermal cycle is defined as a movement from a lower temperature to a higher temperature. The lower temperature is the temperature when the engine is cold and not in operation. After a repeat of a number of thermal cycles, the component is replaced normally. Under the life enhancing control system, Exhaust Gas Temperature (EGT) is measured and it indicates whether the component of interest has reached a certain threshold of its thermal cycle. When this occurs, cooling to this component is increased by increasing, for example, the compressor bleed. Components which can benefit from this are turbine blades, shrouds etc. This cycle can then be repeated until the component reaches a predetermined degree of deterioration.

3.5 GTE Control System for Extended Engine Life

GTEs are most efficiently operated at high Engine Pressure Ratio (EPR), which is a function of engine airflow (W). Large EPR leads to engine stall, however. An engine stall condition occurs for every value of W for a given EPR. Compressor stalls result in a loss of compressor performance, which can vary in severity from a momentary engine power drop (occurring so quickly it is barely registered on engine instruments) to a complete loss of compression (compressor surge as in Figure 6). The working line of the engine then is required to be away from stall and surge regions as far as possible (Figure 6).

The control system of the engine ensures that the engine never reaches stall. However, during transient manoeuvres of the aircraft, sometimes, the engine can reach the stall condition. A control scheme proposed by Schmitt et al [15] potentially offers improved engine efficiency and extended engine life without sacrificing performance. The proposed control system selectively gain schedules the EPR as a function of W so that the engine thrust remains constant at the selected value for a specific flight condition. Further, the controller generates the selected value of thrust at a reduced Turbine Gas Temperature (TGT), thereby extending life of the components.

The control system has two modes of operation: standard mode and Extended Engine Life (EEL) mode. The EEL mode is requested by the pilot during less extreme manoeuvres. The control system determines the current thrust and reconfigures the engine to give the same thrust at values of EPR as a function of W, but with reduced TGT. The scheduling mechanism computes a total differential of EPR as a function of W, so that their ratio always keeps the required thrust constant. The schematic arrangement of the scheme is shown in Figure 9.

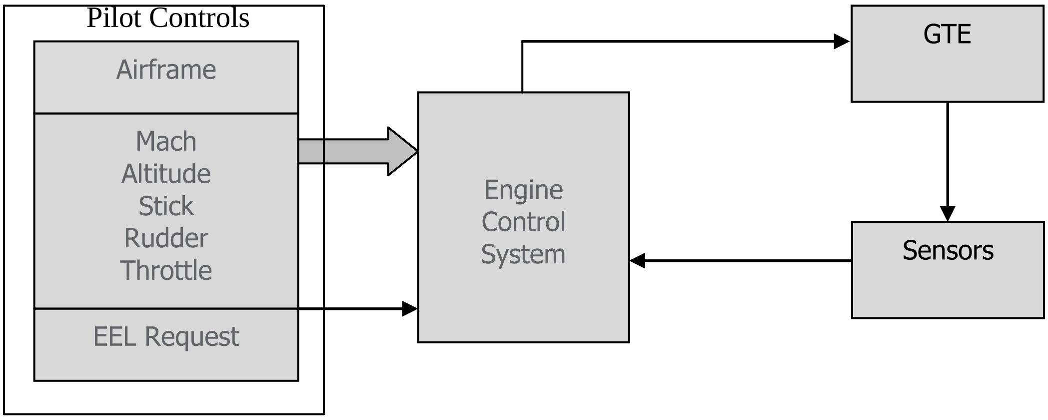


Figure 9: Control schematic for extending life [15]

3.6 Active Clearance Life Enhancing Control

This Section is based on the [17]. Another principal cause of aircraft engine removal is the low Exhaust Gas Temperature (EGT) margin, expended life limited parts (LLP) due to Low Cycle Fatigue (LCF) and slow engine accelerations. EGT margin loss is due primarily to hot section deterioration, i.e. deterioration of components due to exposure to high temperature, while the primary contributors to engine LLP life consumption are high rotor speeds, high peak temperatures, and extended exposure time to high temperature.

As part of life enhancing control strategies in use, Active Clearance Control (ACC) systems have become an integral part of modern commercial gas turbine aircraft engines. They are used to improve performance and lower specific fuel consumption (SFC), thereby lowering turbine operating temperatures and extending engine life accordingly. The spacing, or clearance, between the blade tips on a rotating component and the case or shroud encircling the component directly affects gas turbine performance and efficiency. Engine clearances change during operation of the engine and over the life of the engine, and vary depending on rotor speeds, temperatures, and deterioration. ACC is an attempt to improve engine efficiency (thereby improving SFC, reducing temperatures, extending life, etc.) by manipulating the transient and steady state clearances during operation.

Wiseman et al [17] propose further improving the ACC system by compensating for deterioration or by improving nominal control with increased control authority.

Blade tips and shrouds wear over time due mainly to friction when clearances are too tight. As the engine deteriorates, EGT increases, which accelerates the gas path deterioration process. New engines normally come with a certain amount of cold clearance, and as the engine is used, this cold clearance may increase substantially before the first overhaul. The majority of the wear occurs early in the engine life and that is due to severe takeoffs and rotations, hard landings, etc. [authors] formulate a rule-of-thumb that equates 1 millimetre of clearance to 1°C take off EGT margin. This represents a potential improvement in life (in terms of takeoff EGT margin) if the deterioration could be compensated for by the ACC system. At cruise, 1 millimetre of clearance is worth as much as 0.1% SFC, so 10 millimetres of reduced clearance is worth approximately 1% SFC, showing a potential economic benefit as well.

3.7 Other Strategies

This Section is based on [13]. One of the most critical components in a GTE are the turbine blades which are affected by the temperature of the incoming hot gaseous mixture from the combustor which is measured as TGT. An optimum TGT is necessary for optimum operation and the blades structural viability. Higher temperature leads to the fatigue of the blades and increases SFC while lower TGT decreases the thrust generated. The choice of an optimum value of TGT is further compounded by the fact that the generation of Nitrous Oxides (NO_x) and unburnt hydrocarbons (UHC) has to be within limits governed by legislations. Operational lifetime of the turbines becomes thus linked with TGT which is governed by SFC, thrust and emission control considerations.

To reduce emissions in the first place, OEMs use dry low emission (DLE) combustion technology. One of the promising technologies that were used with DLE was lean premixed combustion. However, the benefits of NO_x reduction comes at a price. As the optimum flame temperature of a lean premixed combustor is close to the lean flammability limit, combustor performance is characterized by a CO/NO_x trade-off. At the combustor design point, both carbon monoxide (CO) and NO_x are below target levels; however, deviations from the design flame temperature cause emissions to increase. This trade-off becomes particularly important during part-load turbine operation, when the combustor is required to run even leaner.

The power output of a gas turbine is directly related to the firing temperature, which is directly related to flame temperature and the rate of thermal NO_x formation. The formation of NO_x increases dramatically when the temperature exceeds 1500 ^oC. As traditional diffusion flame combustor temperatures can exceed 2200 ^oC for brief periods, it is virtually impossible to achieve ultra-low NO_x levels when a turbine is fired with a diffusion flame combustor. This also implies that the turbine blades will be unable to withstand such temperatures, if used. To overcome this problem, low emissions of NO_x, and UHC, can be achieved with thorough fuel-air mixing and control of the adiabatic flame temperature below 1650 ^oC. The peak combustion temperature can be limited to below 1550 ^oC, where NO_x levels can be less than a few parts per million (ppm). However, at fuel-air ratios low enough to achieve such low NO_x concentrations, flames are highly unstable and are susceptible to flame-out or fluctuations, which can cause severe combustor vibrations and fatigue failure of combustion components.

One potential solution of this problem could be the use of staged combustion system [2,13]. The combustor will have a primary and secondary combustor. At low power, the pilot combustors fire up and during full power, the main burners fire up. This has some effect on reducing the emissions. OEMs use aerodynamically stable injectors for the burner system and they have very small ranges of operation. This necessitates the use of multiple stages of burners.

Further, the control of GTE can be optimised by controlling the staged combustion through a predictive control system. Among other factors, the HBVs play an important part in maintaining the GTE temperature. The opening and closing of the HBVs can be controlled using the predictive controller so that when the controller looks forward to anticipate an increase in TGT and to maintain the optimum temperature, the appropriate HBVs at the present instant are opened or closed.

4.0 Conclusion

This report has revealed a number of life-enhancing control strategies for GTEs, many of which are the subject of ongoing research. The benefits of using these schemes have yet to be fully realised. Two approaches, discussed previously, show great promise in improving life of a GTE and specifically merit further investigation. These two approaches are:

- Implementing staged combustion control using predictive control. For this investigation to occur, a detailed analysis of the sequence of opening and closing of the Handling Bleed Valves (HBV) and Variable Inlet Guide Vanes (VIGV) and their effect on the compressor maps of a GTE is required [2]. This should be combined with studying the effect on TET in order to develop a linear model of the staged combustor.

- Use of an adaptive-predictive control scheme.
  For implementing this scheme, the structural models of each component of the GTE and the HUMS sensor data collected by the OEM are required. There appears to be a very real opportunity here for the introduction of synergetic control techniques which take advantage of the valuable intelligence obtained through increasingly sophisticated HUMS methods.

5.0 References

1 Anthenien R.A, US Army Research Lab, http://www.arl.army.mil/www/default.cfm?Action=29&Page=206

2 Breikin T.V., Herbert I.D., Kimb S.K., Regunath S., Hargrave S.M., Thompson H.A., Fleming P.J., Staged combustion control design for aero engines, Control Engineering Practice (14), 2006, pp 387-396

3 Bica B., Akat G., Chipperfield A.J. and Fleming P.J., Multiobjective design of a fuzzy controller for a gas turbine aero-engine, Proc UKACC International Conference on CONTROL '98, Swansea, UK, 1998 pp 901-906

4 Caplin J., Ray A., 36th Conference On Decision & Control, USA, December 1997

5 http://www.darpa.mil/tto/programs/mafc.htm

6 http://www.ecertec.com/electro.htm

7 http://fdrc.iit.edu/research/docs/MAFC_XV_15_Briefing_Final.pdf

8 Ghosh K., Thompson H.A., Fleming P.J., Fuel and IGV Position Optimisation , OMEGA Partnership ,November 2008, UK

9 Guo T.H., Wiseman M.W, American Control Conference, USA, 2001

10 http://karthik3685.files.wordpress.com/2007/11/articles-neural-network1.jpg

11 Kaye M., Dynamic Health and Usage Monitoring System-Programme Update, 15th European Rotorcraft Forum, p 12-15, 1989, Amsterdam

12 Negishi, M., Everything that Linguists have Always Wanted to Know about Connectionism. Department of Cognitive and Neural Systems, Boston University, USA, 1998.

13 Peltier, R., http://findarticles.com/p/articles/mi_qa5392/is_/ai_n21327175,April 2003

14 Rolls-Royce plc, The Jet Engine, 6th Edition, 2005

15 Schmitt T.P, Collins S.L, United Technology Corporation, USA, Patent No 5048285, September 1991

16 Sridhar A., General Electric Company, USA, Patent No. US 7290385B2, November 2007

17 Wiseman M.W., Guo T.H, An Investigation of Life Extending Control Techniques for Gas Turbine Engines, proceedings of American Control Conference, June 2001