TURBINE ENGINE HOT SECTION PROGNOSTICS

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Abstract: The design life of engine hot section components is typically shorter than their cold section counterparts, due to the fact that they have to operate under elevated temperatures and stresses. Previously unseen failure modes are being discovered due to the increasing demand for modern engines to operate at higher temperatures and stresses, coupled with the use of new materials for the engines. These unanticipated failure modes can keep engines from achieving their expected design life and may even result in loss of engines. This paper describes an integrated prognostic approach designed to monitor hot section component degradation under elevated temperature, pressure, and corrosion, as well as to infer their useful remaining life. This approach combines both safe life and damage tolerance concepts, and takes into account of all the common hot section failure mechanisms such as creep, oxidation, low and high cycle fatigue, and corrosion. Successful integration of this approach into modern Prognostic and Health Management (PHM) systems can reduce the cycle cost for both the military and the commercial gas turbine engines while maintaining the equivalent safety.

Key Words: Creep; Damage tolerance; Engine hot section; High cycle fatigue; Low cycle fatigue; Oxidation; Prognostics; Safe life

Introduction: Traditional engine health maintenance and life management relies mostly on Time Based Maintenance (TBM), which is done by tracking the operating time and cycles of the engine. Maintenance for a component is performed based on a fixed operating hour/cycle schedule, and/or using exceedance data from basic instruments and algorithms. These maintenance and retirement schedules are typically derived from material properties and fatigue data, based on the assumption of worst-case usage. To help ensure safety, the life limits of flight critical components represent only a fraction of the probable usage that can accumulate before failure indications arise. As such, it is generally referred to as the Safe-Life (SL) approach. The SL approach does not account for the component that fails early or would have lasted for many times the safe life limit.

To minimize the possibility of early component failures, diagnostics are employed for flight critical components. Diagnostics in TBM consists of visual inspections and analysis of operator reports, sometimes aided by data on temperatures, vibrations, and gas path properties. Empirical limits are set for individual measurements as to determine whether a fault is present. Component health determination is often based upon circumstances as determined by flight line or operational personnel. This type of health management is sometimes referred to as the Damage-Tolerance (DT) approach. It is now well understood that TBM-driven lifing of engines leads to both costly unnecessary retirements and maintenance, as well as continued operation of engines that have suffered degradation that may endanger crew and mission performance.

The ability to properly diagnose engine hot section components that are failing due to unknown causes, or prematurely depends on new sensor technologies that can characterize and localize the component that is damaged or degrading. Examples of such sensor technologies include optical combustion constituent characterization, optical pyrometry to determine and map the temperature of blades surfaces, dynamic pressure sensing of combustion stability and inter-blade pressure profiles, bearing vibration diagnostics, electrostatic debris monitoring, and fuel nozzle thermal/acoustic signatures.

One such new sensor technology is an optical system developed by Meggitt/Vibro-Meter that provides enhanced hot section diagnostic and prognostic capability. This system detects the photonic emissions of the combustion flame, and filters the signal to classify and quantify the constituents of the flame. It is believed that this signature can be associated with hot spots, fuel contamination, uneven flame patterns (pattern factor), and upstream (nozzle and compressor) problems that lead to hot section degradation.

Diagnostic systems can be further enhanced by the incorporation of prognostics, which is the enabler for Prognostic Health Maintenance (PHM) by accurately relating the detected fault to the remaining useful life of a component. This requires the development of a reliable prognostic strategy that integrates the history of diagnostics in conjunction with the operational/structural usage, and the physics of fault progression.

The Useful Life Remaining (ULR) concept, which is illustrated in Figure 1, is designed to provide a prognostic life management system that can maximize the useful service life of engine hot sections while providing a greater level of safety than the current TBM lifing and inspection approach does. This goal is achieved by combining the continuous analysis of state/usage parameters and advanced diagnostics capabilities.

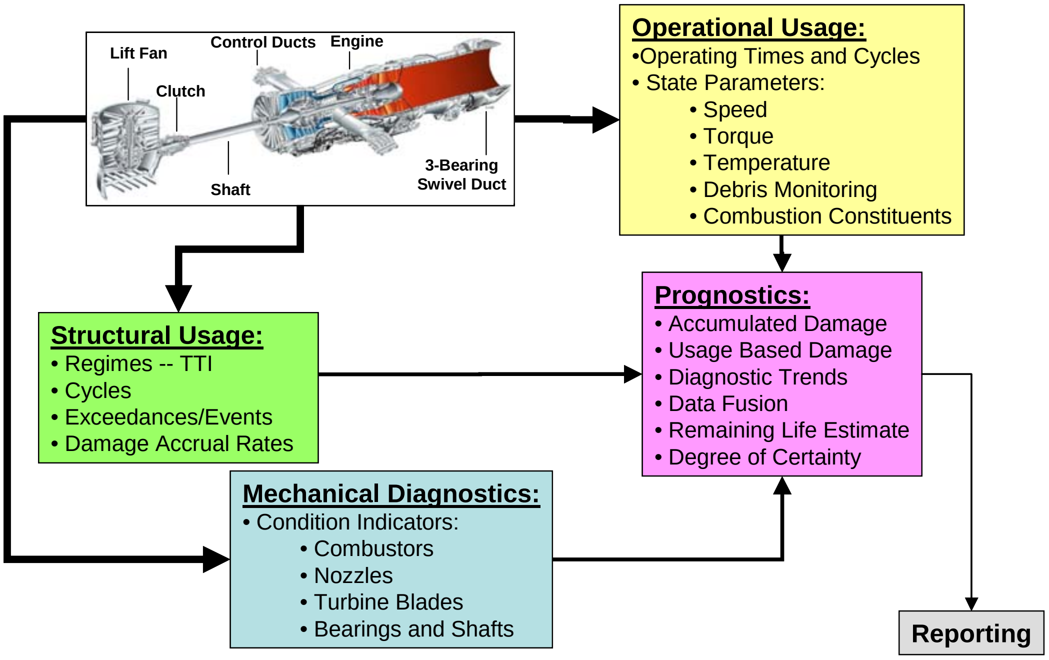

Figure 1. Overview of the ULR prognostic concept.

Hot Section Failure Mechanisms: The engine hot section is generally referred to where the components are subject to high temperatures, such as in the combustor and turbine. These components include: nozzles, combustor liners, transition pieces, 1st and 2nd stage vanes and blades of the gas turbine. Historically turbine blades are the primary contributor to the maintenance cost of gas turbine engines [1, 5, 11].

In general, hot section life is known to be critically dependent upon the following factors:

- Maintaining temperatures within specified ranges
- Maintaining uniform spatial distribution of temperatures at the turbine inlet
- Minimizing incidents of overspeeding of rotating components
- Avoiding/managing corrosive fuel/air mixtures
- Hot start intensity and frequency

Due to elevated temperatures and operational stresses, the design life of a hot section component is only about half as long as that of a cold section component. As engines are being operated at higher temperatures and stresses, and with the use of new materials, previously unseen failure modes are being discovered. These unanticipated failure modes can keep engine components from achieving their expected design life [9, 13, 14]. Common failure mechanisms, which can arise from normal operations or improper management of the engine, include:

- Low Cycle Fatigue (LCF)
- High Cycle Fatigue (HCF)
- Creep/Rupture
- Oxidation
- Corrosion
- Foreign Object Damage (FOD)

The first four mechanisms are typically related to the engine design, while the last two can be attributed to the operating environment.

Low Cycle Fatigue (LCF): Engine hot section components develop so called Thermo-Mechanical Fatigue (TMF), which is a unique type of fatigue because the material is simultaneously subjected to fluctuating loads and temperatures. Isothermal life prediction techniques are often not applicable to TMF because different damage mechanisms can arise under extreme temperature conditions. This type of fatigue failure can be furthered classified into In-Phase (IP) TMF that occurs when the maximum strain and peak cycle temperature coincide, or Out-of-Phase (OP) TMF where the maximum strain and lowest cycle temperature coincide. One example of OP TMF cycles is the TMF damage occurred on the leading edge of a gas turbine blade from repeated turbine starts and stops [4, 9].

High Cycle Fatigue (HCF): HCF represents metal fatigue that results from cracking or fracture phenomenon at stress levels much lower than stresses associated with steady loading. HCF can result from a combination of steady stress, vibratory stress, and material imperfections that initiate the formation of a small microscopic crack. Since today’s advanced turbomachinery blading is designed to have high steady stress levels, HCF occurs because of high mean stress - low amplitude vibratory loading of the airfoils. The most common unsteady aerodynamic flow-induced vibrations are wakes generated by an upstream airfoil row. A reduction in the relative velocity in the wake causes a decrease in the absolute velocity as well as an incidence increase to the downstream stator vanes, which then leads to fluctuating forces on the downstream airfoils [4, 9, 13].

HCF resulting in the loss of gas turbine engine blades or disks is currently the leading surprise failure mode. This is because of the design of high thrust-to-weight ratio engines, accomplished by increasing the mass flow and utilizing fewer parts.

Oxidation: As a result of the extreme temperatures, turbine blades are quite susceptible to high-temperature oxidation. Oxidation problems occur due to the formation of brittle oxide surface layer on the turbine blades, which can lead to premature fracture damage in fatigue. Turbine blades rely on cooling air delivered from upstream in the engine to cool the airfoils and to provide a film of cooler air to protect the airfoil from high temperature. If the continue flow of cooling air is compromised or if the external temperature environment changes, the blades can fail before their design life [3, 6].

Creep: Creep is permanent material deformation under stress. A certain amount of thermal activation energy is required for creep to occur. Under high temperature conditions, materials are weakened thus the creep process accelerates. Creep can initiate small cracks in components, which can then grow in size and eventually lead to component failures. These failures can be catastrophic, especially when the failed components are compressor or turbine rotors. This crack growth and component failure process is known as stress rupture. The evolution of creep damage can be represented by a creep curve consisting of three stages: primary (transient), secondary (steady-state) and tertiary (unstable) which then leads to rupture [2, 3, 4].

Creep rupture occurs primarily due to microcraking and void growth along grain boundary, and is associated with boundary sliding. In single crystal blades where there is no grain boundary, failure is associated with void growth and the subsequent microcracking of voids. The time to rupture (t_r) is often found to increase linearly as the steady-state creep rate ($\dot{\varepsilon}_s$) decreases, based on the Monkman-Grant relationship:

$$t_r = M \frac{1}{\dot{\varepsilon}_s}$$

where M is a material dependent variable, ranging from 0.1-10. As $\dot{\varepsilon}_s$ increases, the creep curve gets more vertical and therefore the time to rupture would decrease.

Creep strains in the low temperature range (less than 30% of the material's melting point) are usually very low and as such creep rarely leads to failure. For intermediate temperatures (between 40% to 90% of the material's melting point), the steady-state creep rate can be shown to be a power-law function of stress (σ) and temperature (T):

$$\dot{\varepsilon}_s = AB\sigma^a e^{-(Q_C / RT)}$$

where A is a constant, B and a are material-dependent constants, R is the universal gas constant (≈ 8.314 JK-1mol-1) and Q_C is the material-dependent activation energy for creep to occur.

Figure 2 shows example of five creep curves for several different temperatures and stresses. These curves are derived using the equation above with S-590 alloy properties.

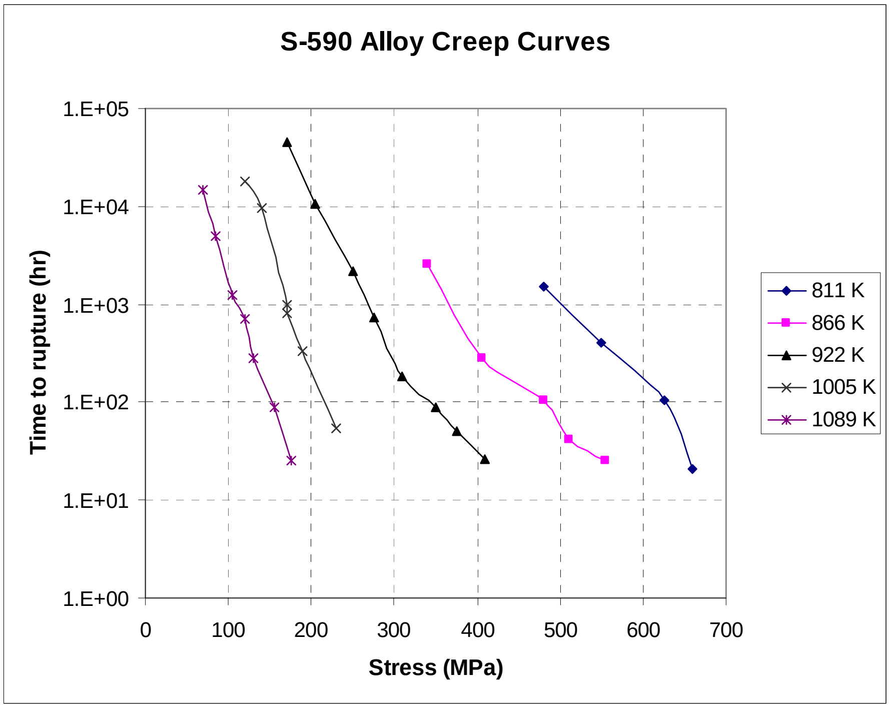

Figure 2. Example of creep curves under various temperature and stress conditions. Shorter time to rupture occurs under higher temperature and stress.

After unloading, all materials demonstrating creep also display creep recovery, i.e. some of the strain will gradually disappear. For metals however, the recoverable strain is usually quite small (≤ 1%) and can be ignored.

Generally speaking the performance of current industrial gas turbines is limited by the temperature and strength capabilities of the materials used. Since industrial gas turbines are designed to run continuously for extended periods of time, the primary failure modes for the blades are HCF and creep. As such, lifing research has been concentrated on developing methods for describing the effect of these phenomena on blades. On the other hand, jet engines are cycled between start up and maximum thrust for each flight (about 10 flights a day for commercial aircraft). Therefore LCF is the dominant failure mechanism, though some unexpected failures can be attributed to HCF.

Several damage control approaches have been proposed in the past to mitigate the hot section failure modes, and some have been integrated into the Full Authority Digital Electronic Control (FADEC) module for modern engines. One such example is the Life-Extending Control (LEC) approach originated from rocket engines, which was designed to control LCF/HCF and creep by optimizing the engine fuel flow rate [13, 14].

ULR Prognostic Model: As mentioned earlier, lifing models can generally be classified into two categories: total life and crack growth. Total life models, such as the Palmgren-Miner model, only calculate the time to failure and do not consider the way failure is reached. These models are representatives of the SL approach, aiming to retire a component before a crack initiates. To ensure safety, a substantial amount of conservatism is built into a total life model since it is an open-loop approach [7, 8, 9, 13, 14].

In contrast crack growth models accept the presence of material defects and aims to monitor crack growth. Because of this, they are also known as the DT approach. In this approach components are removed before the crack becomes unstable. Local analysis, using stress histories at specific locations on the component (i.e., locations of crack initiation or high stress points) is performed based on crack growth models. As such they are only applicable to certain locations. Recent sensor advancements enable some level of monitoring of crack initiations and their subsequent growth. However the effectiveness of this approach is not fully understood due to the uncertainty associated with the data. It is further complicated by the fact that most direct measurements are not possible due to the extreme environment in the engine hot section.

Temperature is the key factor in hot section component life. Heat transfer models are usually used to model the distribution of component temperatures. The metal temperatures are then used in conjunction with the pressure and centrifugal loads, as well as the material stress-rupture properties to determine the hours of life used or remaining, typically through finite element analysis. These models however, are difficult to implement for automated real-time analysis.

The hot section component ULR prognostic model incorporates both SL and DT approaches, as shown in Figure 3. In this model, the parameter data such as temperatures, pressures, speeds, torques, load factors, vibrations, and stress waves from various sources are utilized to compute the time in each operating condition for each flight. This usage data, combined with OEM supplied damage rates, are then used to compute the projected time to retirement for each component.

The acquired data is also used by the crack monitor to detect any presence of cracks. If no crack is detected, the projected remaining life of a component is reported based on the SL estimate. Once a crack is detected and confirmed, the crack growth estimator will use the data to determine the rate of crack propagation and to report the time to failure, based on various mission spectra.

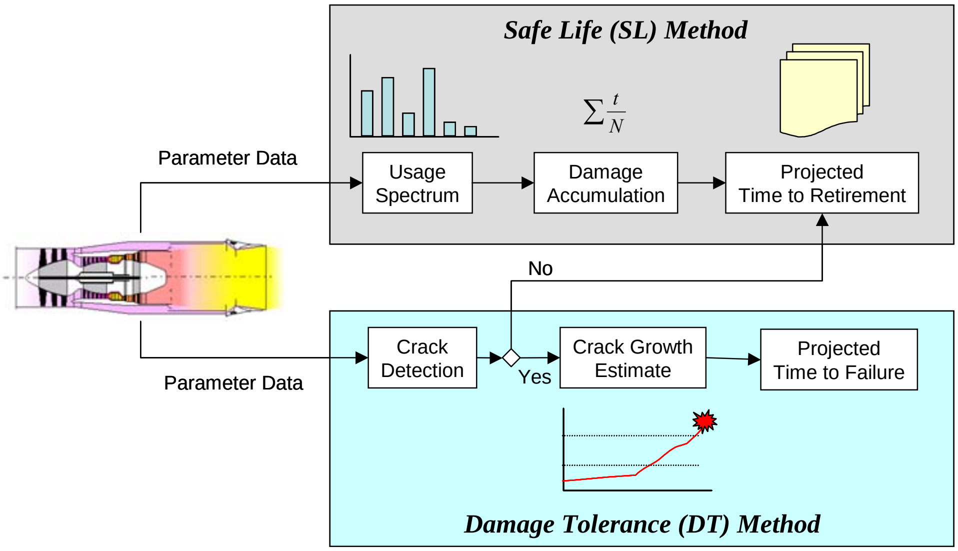

Figure 3. The ULR prognostic model includes both safe life (SL) and damage tolerance (DT) methods.

Damage accumulation in the ULR model for engine hot section components incorporates the following algorithms:

For LCF/HCF, damage accumulation is done by Miner's rule:

$$D_f = \sum \frac{n_i}{N_i}, \qquad i = 1,...m$$

where D_f is the accumulated damage, n_i is the number of cycles at a given load, N_i is the number of cycles to failure, and m is the total number of load conditions. End of life is implied when D_f reaches one.

Temperature dependent creep can be accumulated in a similar manner as described below:

$$D_c = \sum \frac{t_i}{t_{r\,i}}, \qquad i = 1,...m$$

where D_c is the accumulated creep damage, t_i is the time at a given strain and temperature, t_{ri} is the time to rupture, and m is the total number of strain/temperature combination.

Turbine blade oxidation damage accumulation is calculated as:

$$D_o = \sum D_o^l, \qquad l = 1,2,3$$
$$D_o^l = \sum \frac{t_i}{t_{o\,i}}, \qquad i = 1,...m$$

where D_c is the accumulated oxidation damage, for a blade consisting of three layers of different materials it is the sum of damages from each layer, t_i is the time at a given temperature, t_{oi} is the time to failure, and m is the total number of thrust/temperature combination.

Since components in the hot section are subject to the combination of the above three failure modes, they are tracked by the ULR model. At any given time, one of the three will be the dominant failure mode (i.e., the highest accumulated damage) and the final component life is projected based on the damage from this dominant mode.

Crack detection and tracking involve detecting crack initiations, diagnosing the location and severity of a detected crack, and predicting the crack growth rate. Typically this is done by collecting and analyzing data from one or more sensors. For example abnormal stress waves, vibrations, and/or uneven temperature distributions may indicate a cracked blade.

The ULR prognostic model provides a data fusion algorithm that combines various indicators from multiple sensor sources to produce a component health indicator. The prognostic model provides the ability to determine if a trend is developing in the health indicator for a given component. Furthermore, it includes the ability to determine how quickly that indicator is approaching (or might cross) a preset limit, based on projected usage.

Flame Contaminant Detection (FCD): Corrosive contaminants such as sodium in the combustor can weaken parts and thus reduce life. An optical system developed by Meggitt/Vibro-

Meter has the ability to detect the photonic emissions of the combustion flame and filters the signal to classify and quantify the constituents of the combustion flame [10]. This signature can be associated with hot spots, fuel contamination, uneven flame patterns (pattern factor), and upstream (nozzle and compressor) problems that lead to hot section degradation.

Extensive data analysis showed that the FCD is capable of detecting sodium contaminants for the entire gas turbine load range, and has the potential for quantifying the amount of contaminants in the combustor. Figure 4, which represents one of the results obtained in this study, shows the amounts of sodium contaminant predicted based on the FCD data. The result indicates that the predicted sodium amounts match the actual amounts injected to the combustor relatively well.

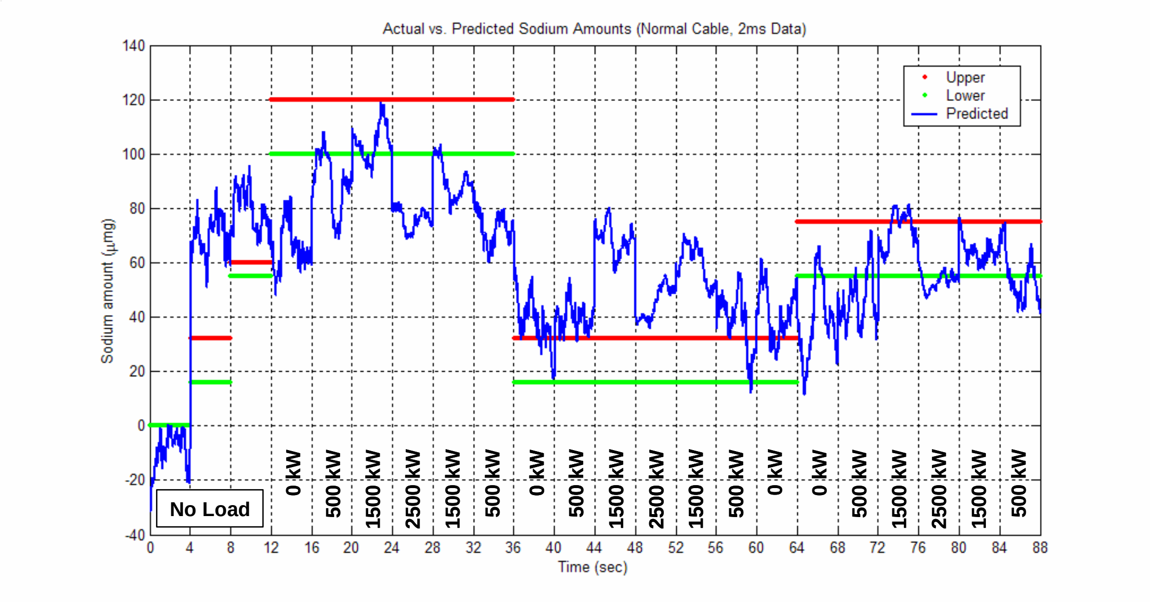

Figure 4. Actual vs. predicted sodium contaminant amounts.

Summary: The ULR prognostic methodology combines both SL and DT approaches to achieve complete and accurate prognostics. The SL approach utilizes damage accumulation to determine the safe-life limit for a component, while the DT approach relies on using sensor data to detect and monitor cracks.

Damage accumulation in the ULR methodology is performed through the use of aircraft/engine parameter data mapped to a set of component load conditions. Component load data, damage rates, and their failure modes are then combined to derive damages after each flight. Damages due to LCF/HCF, creep, and oxidation are monitored and accumulated.

Crack detection and monitoring is done by the fusion of sensors designed to identify the presence of abnormal stress waves, vibrations, pattern factors, discharges, in conjunction with a physical model of the engine hot section. When no crack is present, the ULR prognostic model projects the component life based on damage accumulation. Once a crack is detected, the ULR model switches to crack tracking prognostics for useful life remaining estimation. This functionality provides a safeguard to failures that might occur before the safe-life limit, and addresses the safety and reliability concerns among aviation community.

Investigation and testing of the flame contaminant detector showed that it is capable of detecting sodium contaminant for the entire gas turbine load range. In addition it shows the potential for quantifying the amount of contaminant in the combustor. This capability is especially important for establishing the relationship between hot section degradation and various contaminants in the engine. Data from the frame detector can also be used to infer temperatures, which is a crucial parameter for hot section component lifing.

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