Enhancing Operational Availability of Gas Turbines through Effective Maintenance Planning Using Advanced Fault Diagnostics

Sampath Suresh, Pericles Pilidis and Riti Singh

[a]*Centre for Propulsion, School of Aerospace, Transport & Manufacturing*
Cranfield University, Cranfield, Bedfordshire- MK43 0AL
United Kingdom

INTRODUCTION

Marine gas turbines have been in service for more than three decades and have proved to be reliable and offer significant advantages to the user. Despite well-proven reliable features of these machines their operation in hostile marine environment has been a cause for concern, both to the manufacturer and the user. All turbo machinery gradually experience recoverable and non-recoverable losses in performance with time. Typically recoverable losses are associated with compressor fouling and to a large extent be rectified by water/chemical washing or, more thoroughly, by mechanically cleaning the compressor blades and vanes after opening the unit. Non-recoverable loss is primarily due to increased turbine and compressor clearances and changes in surface finish and airfoil contour and needs to capital repairs to restore performance. Therefore the maintenance efforts are essentially directed towards recoverable losses. This paper presents an overview of the some modern diagnostics techniques and how they could influence the vital decisions regarding maintenance and manpower. The methods are explained with suitable case studies.

MAINTENANCE PLANNING

There are many factors that can influence equipment life and these must be understood and accounted for in the operators maintenance planning. Factors like the starting cycle, power setting, fuel and level of steam or water injection factors in determining the maintenance interval requirement as these factors directly influence the life of the critical gas turbine parts. The ideal approach would be to establish a maintenance factors based on some baseline parameters and work out a schedule and any deviation from the baseline operation would necessitate a increased maintenance level e.g a maintenance factor of 2 would indicate a maintenance level which is half the baseline level[1]. Advance planning for maintenance is a necessity and proper implementation of the planned maintenance and inspection provides direct benefits in reduced forced outages and increased starting reliability, which in turn reduces unscheduled repair

ISSN:1791-4469

downtime. The primary factors which affect the maintenance planning process are shown in Fig-1 and the operating mode will determine how each factor is weighted.

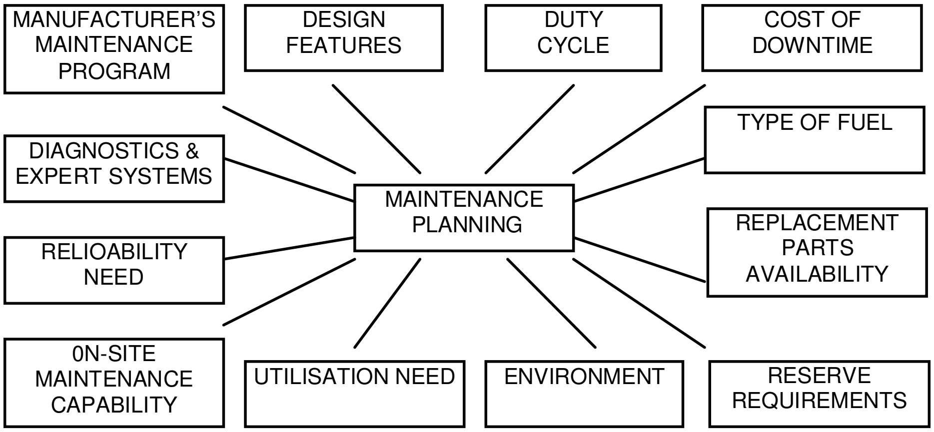

FIGURE 1. Factors Affecting Maintenance

FACTORS INFLUENCING MAINTENANCE AND EQUIPMENT LIFE

Parts unique to the gas turbine requiring the most careful attention are those with the combustion process together with those exposed to high temperature from the hot gas discharged from the combustion system. They are called the hot gas path parts and include combustion liners, end caps, fuel nozzle assemblies. Gas turbine wear in different ways for different service duties like damage caused due to continuous duty application – Rupture, Creep Deflection, High Cycle Fatigue, Corrosion, Oxidation, Erosion, Rubs/Wear, Foreign Object Damage etc. and Damage caused due to cyclic duty application- Thermal Mechanical Fatigue, High Cycle Fatigue, Rubs And Wear, Foreign Object Damage(FOD) etc.

Some manufactures base their maintenance requirements on the number of starts and hours, which ever criteria limit is reached first determines the maintenance interval. Another approach which is adopted by other manufactures is the Equivalent number of Operating Hours(EOH) with inspection interval based on equivalent hour count. However it is believed that this logic can create an impression of longer intervals, while in reality more frequent maintenance inspections are required[1]. In addition, operating conditions other than the standard startup and shutdown sequence can potentially reduce the cyclic life of the gas path components and rotors, and if present will require more frequent maintenance and parts refurbishment and or replacement. Firing temperatures changes occurring over a normal startup and shutdown cycle, light-off, acceleration, loading, unloading and shutdown all produce gas temperature changes that produce corresponding metal temperature changes (fig-2).

Thermal and mechanical fatigue testing has revealed that the number of cycles that a part can withstand before cracks occur is strongly influenced by the total strain range and the maximum metal temperature experienced. Any operating condition that significantly increases the strain range or maximum metal temperature over the normal cycle conditions will act to reduce the fatigue life and increase the starts based maintenance factor. Trips from load, emergency starts and fast loading will impact the starts-based maintenance interval. This again relates to the increased strain range that is associated with these events. Emergency starts where the engine is brought from standstill to full load conditions in less than five minutes will have parts life effect equal to 20 normal start cycles and a normal start with fast loading will produce maintenance factor of two[1].

In general, axial flow compressor deterioration is the major cause of loss of gas turbine output and efficiency. Recoverable losses attributable to compressor blade fouling, typically account for 70-85% of the performance losses seen. Fortunately, much can done through proper operation and maintenance procedures to minimize fouling type losses. Online compressor wash systems are available and are used to clean heavily fouled compressors. Other procedures include maintaining the inlet filtration system and inlet evaporative coolers, periodic inspection and prompt compressor bla+++de repair. Considering the maintenance aspects discussed above, an adjustment from these maximum intervals may be necessary, based on the specific operating conditions of a given application. Initially, this determination is based on the expected operation of a turbine installation, but this should be reviewed and adjusted as actual operating and maintenance data are accumulated. The condition of the hot-gas-path parts provides a good basis for customizing a program of inspection and maintenance.

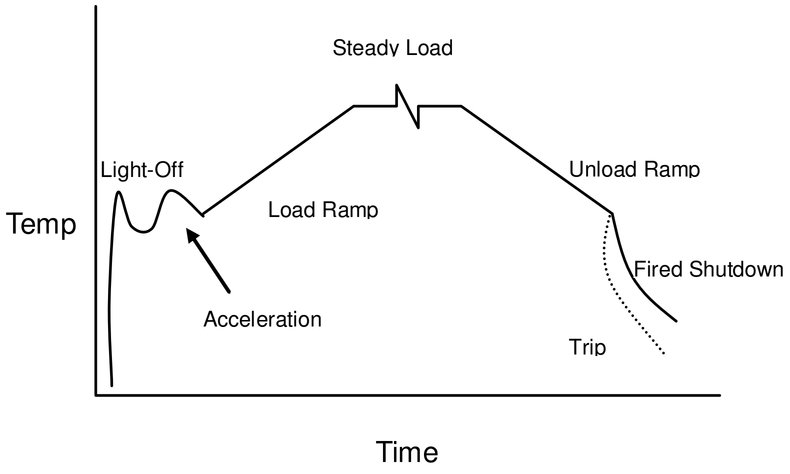

FIGURE 2. Turbine Start/Stop Temperature Profile

NEED FOR ENGINE FAULT DIAGNOSTICS

When a forced outage is experienced, the down-time incurred depends on the period required to complete the necessary repair or maintenance action. The largest contributors to forced outage rates are often engine support systems such as control and fuel systems. The down-times associated with these systems can be managed to acceptable levels by design redundancy and the holding of appropriate spares. Advances in instrumentation and microprocessor-based controllers can be expected to contribute to further improvements in the availability of engine support systems. In contrast, the major gas-path components such as compressors and turbines have high reliabilities. However, when a forced outage is caused by deteriorations of these components, the down-time experienced can be large (figure-3). Both the high cost of such components and the low likelihood that they will be required means that they are often not held as spares by the operators [2].

ISSN:1791-4469

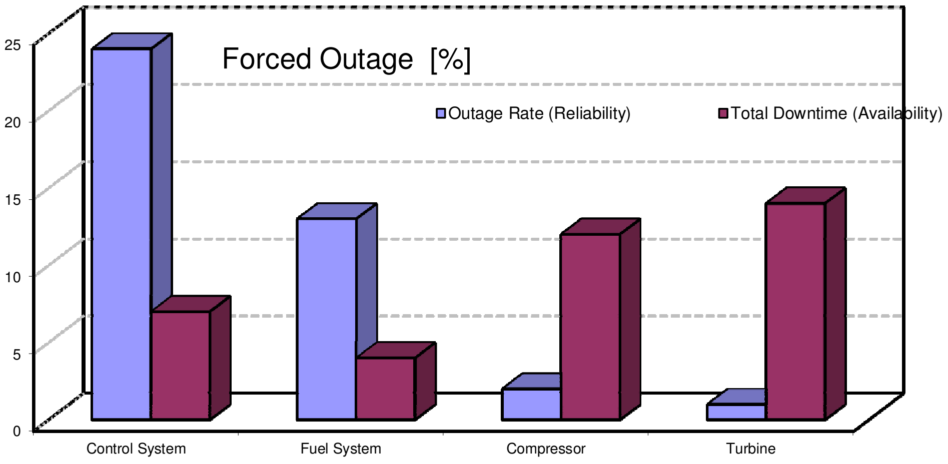

FIGURE 3. Forced outage and Component availability

One of the major challenges faced by a marine engineer of an operational ship is to strictly adhere to the maintenance schedule. Unexpected/unpredictable operational commitments often necessitate postponing a particular maintenance action compounded by the fact that a particular port may not have adequate facilities. A diagnostics tool which could provide adequate warning on the engine condition would be useful in planning the maintenance schedules. Overall a simulation and diagnostics tool would help in-

(a) Optimising maintenance intervals for specific engines based on the condition.
(b) Prioritise tasks to be performed during a planned maintenance event.
(c) Reduce overall life cycle costs of engines from installation to retirement.
(d) Enhanced availability of engines within a fleet.
(e) Engineering justification for scheduling maintenance actions.
(f) Improved safety associated with operation and maintenance of gas turbines.
(g) Training maintenance personnel on the good maintenance practice understanding degradation in of engines.

ENGINE PERFORMANCE-SIMULATION BASED DIAGNOSIS

Simulating the performance of an engine using mathematical model which relies on basic aero-thermodynamic principles to predict a reasonably good level of engine performance forms the basis for these types of diagnostics. The model like its physical counterpart, can be made to simulate deterioration over a period of time attributable to various factors like fouling, foreign object damage, corrosion, erosion etc. causing shift in performance parameters. However, ascertaining the deterioration quantitatively is always a challenging task and is an important step towards calculating the implications and then planning an appropriate maintenance strategy.

The methodology used to obtain degradation/faults of components using the measured or the gas path parameters is called the Gas Path Analysis. The fundamental concept of GPA is that the physical problems (i.e. fouling, erosion, FOD etc..) would cause loss of component performance(change in component efficiency and flow capacity) which would manifest itself in the form of change in the operating parameters which can be measured like temperature, pressure, spool speeds etc..[3]. Schematically GPA can be represented as shown in figure-4.

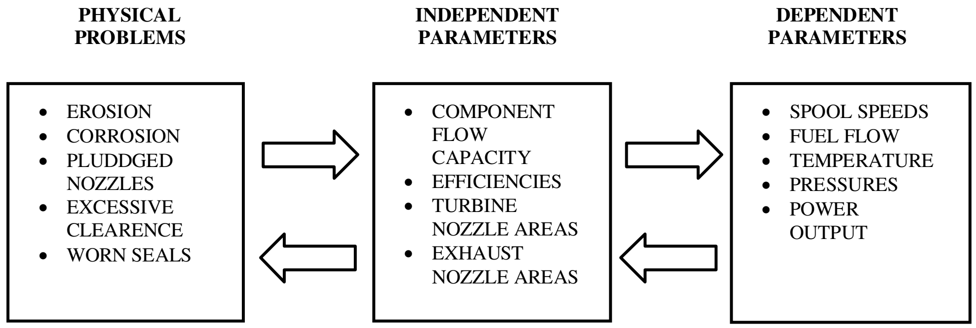

FIGURE 4. Concept of Gas Path Analysis [3]

Mathematically, the relation between the independent parameters and the dependent parameters can be represented by a set of differential equations and the coefficients of the differential equations in a matrix form is called the Influence Coefficient Matrix (ICM), in real life situations we would have the measurements from the engine and therefore the change in component performance could be determined by inversing the ICM to obtain FCM and multiplying it with the measurements [3]. Improvements in engine diagnostics can in theory be achieved simply by adding more and more reliable instrumentation to monitor the engine's health. However, the instrumentation itself has its own mean-time to failure and in real life situation the presence of instrumentation noise and bias cannot be ruled out. Additionally, inappropriate or badly maintained instrumentation can lead to the detection of spurious faults, leading to unnecessary expensive maintenance actions. Several variants of GPA , like the use of Kalman filters(KF), Extended Kalman Filters(EKF) and Weighted Least Square (WLS)[5,6] have been developed over the years and implemented successfully by engine manufacturers. Other modern diagnostics techniques using Genetic Algorithm (GA) and Artificial Neural Network (ANN) have been used by Sampath et al [7], Fuzzy Logic, Bayesian Belief Networks (BBN) etc. have also been developed and used. Fundamentally all the methods use the performance simulation method to isolate the fault.

ENGINE PERFORMANCE ASSESSMENT- CASE STUDIES

The main advantages of the above fault diagnostics methods are their ability to account for noise/sensor bias and non-linearity of the engine performance model. Another important aspect is the ability to quantify the faults detected which help in analyzing the implications of such faults and the magnitude of its influence on the overall engine performance. In order understand the effects of the fault certain test cases have been designed using two engine models. The first one is a simple cycle turboshaft engine of appx. 25 MW capacity (Pressure ratio -18, mass flow of 70kg/s and TET of appx. 1600K) and the other engine considered is a more complex cycle Intercooled-Recuperated three shaft engine of appx. 25 MW power (PR-11, mass flow -126 kg/s and TET- 1383K). The engine simulations were undertaken using a generic performance simulation software tool called "Turbomatch" at Cranfield University. Table-1 shows the levels of component performance parameter change for a given fault condition. Having decided the deteriorations levels, six fault scenarios are considered as shown in table -2. The aim of the study is not to compare the performance of these engines, but to give an idea of the effect of the faults on the engine performance which will affect the overall life cycle costs.

TABLE 1. Values of faults implanted in test cases

Degradation	Efficiency change	NDMF change
Compressor fouling	-2.00	-5.00
Compressor erosion	-1.00	-2.00
Turbine erosion	-1.00	+2.00
Turbine deposition	-1.00	-2.00
FOD	Same as fouling (Less Magnitude)	
Corrosion	Same effect as erosion	

TABLE 2. Test Cases for sample

Case	Types of Faults	
	ICR-Turboshaft (25 MW)	**Turboshaft (25 MW)**
Case-A	LP Compressor Fouling	Compressor fouling
Case-B	Both Compressor Fouling	Compressor Erosion
Case-C	HPT & LPT Erosion	Compressor Turbine Erosion
Case-D	Both Compressor Fouling and HPT erosion	Power Turbine Erosion
Case-E	Both Compression Erosion	Comp. Fouling and CT Deposition
Case-F	HPT Deposition	Compressor and CT Erosion

TABLE 3. Effect of Deterioration and running restored

CASE	DETERIORATED		RESTORED	
	Δ Power(%)	Δ s.f.c(%)	Δ TET (°C)	Δ s.f.c(%)
CASE-A	-6.13	2.54	38.00	1.12
CASE-B	-2.40	0.85	18.00	1.20
CASE-C	-1.10	0.76	11.00	0.75
CASE-D	-0.79	1.46	10.00	1.45
CASE-E	-7.80	3.00	46.00	2.40
CASE-F	-6.90	3.40	43.00	2.20

The results of the simulation for the Turboshaft engine are tabulated in Table -3 which clearly brings out that in all case shows the effects of deterioration leads to power short fall and an increased specific fuel consumption (s.f.c). the situation worsens when the engine is run restored i.e. in order to make up for the reduced power the engine is run hotter (higher TET) this would have an adverse effect on the creep life of the hot end components. Overall, the degradation results in increased fuel consumption (reduced range), reduced hot section creep life and reduced surge margin imposing severe limitation on acceleration. In interesting outcome of the ICR-Turboshaft simulation is that the s.f.c improves due to increased temperatures as the result of degradation. It is mainly because, the recuperater recovers the exhaust heat thereby reducing the fuel burn. However, the improved s.f.c is offset by the reduced hot end component life.

ENGINE LIFE CYCLE COST & MANAGEMENT- CREEP LIFE APPROACH

Based on the design operation and maintenance philosophy for a marine gas turbine and the degradation it undergoes, the creep life for the turbine blades is considered as one of the life limiting criteria. Sophisticated mathematical models for life cycle cost analysis have been proposed by Spector[8] considering various aspects like the Initial investment cost, Cost of financing, variations in equipment availability, cost of fuel , operation costs etc… at this point the need for an accurate input data needs no emphasis. The LCC itself is a complicated subject and the application of the above criteria for naval marine gas turbines is difficult due to the nature of application.

Material deterioration is the general limiting factor in defining the maintenance schedules of installations and a critical parameter in judging the further operability of high temperatures installations. Higher firing temperatures reduce hot gas path lives while lower firing temperature increased parts lives. This provides an opportunity to balance the negative effects of higher load operation by periods of operation at part load. However, It is important to recognize that the nonlinear behavior described will not result in a one for one balance for equal magnitudes of over and under firing operation. High temperature installation not only suffers from creep but also from low cycle damage and hot section corrosion. However, hot section corrosion is not very critical as it is usually dependent on the quality of the fuel and marine gas turbine use LSHSD which contains very low sulphur and negligible vanadium. Fatigue would be an important failure mode if there are very frequent power changes (like in military aircrafts).

Naval ships usually operate for long periods at different power setting depending on the role of the ship. Therefore the residual life of the marine gas turbine is considered with respect to creep life for the purpose of analysis and aims to specify creep life as functions of engine exploitation pattern and engine degradation.

For marine gas turbines the time spent at various power regimes is an important consideration followed by the temperature. Current generation advanced GTs offer higher power-to-weight due to increase pressure ratios and temperatures, the time spent at higher temperature is significantly less for a marine gas turbine, nevertheless, it reduces the creep life. Times spent at different temperature are varying and therefore the mission profile should be known. All Naval ships do not have same mission profile and depend on its role e.g a ship carrying out a an antisubmarine or minesweeping operation would spend majority of its exploitation at lower regimes and some small missile boats are used of fire and run and would operate at higher regimes periodically. Figure-5 shows some arbitrarily chosen mission profiles for the purpose of study. These mission profiles have been applied to an imaginary ship fitted with one intercooled recuperated turboshaft engine for main propulsion.

The mission profiles in figure 5 are simulated assuming that each mission lasts for 100 hours. The creep life consumed is calculated using the procedure show an Appendix 'A' and results are shown in table-4. The principle of balancing the negative effects of higher load operation by periods of operation at part load is used. However, it should be recognized that the non-linear nature of the engine and the variation in parameters does not result in one for one compensation for over and under firing. By obtaining the creep damage factor for a particular profile one can identify the actual life usage of the hot components by dividing the actual hours of operation of the engine by the damage factor. Let us consider a case, in which an engine was designed to operate at full power for 100hrs. However, if the same engine is operated according to operating profile shown in CASE-A (fig-5) which is benign compared to what it is designed for, results in a creep life usage factor of 19.68. Therefore the total duration operated divided by the creep life usage factor would result in a consumption of only 5.08 hrs. Likewise, it can be observed that other profiles also result in increased exploitation periods which is important to understand particularly for inspection of hot end components. The results for various cases is shown in table-4.

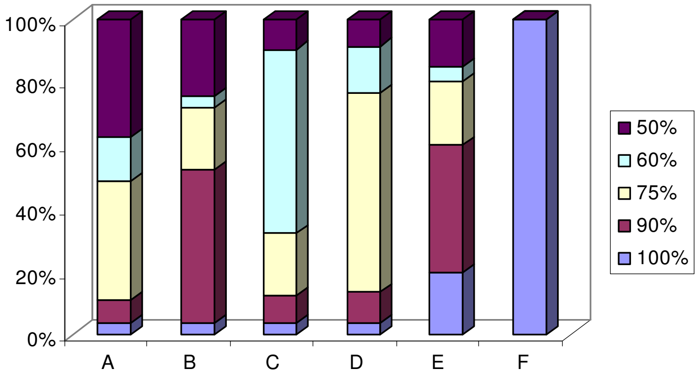

FIGURE 5. Mission Profiles

TABLE 4. Creep Life Usage

Case	Creep Life Fraction	Life Consumed /100 Hours of Operation
Case-A	19.68	5.08 Hours
Case-B	4.12	24.27 Hours
Case-C	15.99	6.25 Hours
Case-D	10.94	9.14 Hours
Case-E	2.51	39.84 Hours
Case-F	1	100 Hours

CONCLUSION

This paper proposes the use of advanced engine fault diagnostics techniques which could be used for planning maintenance activities and manpower. The ability of the diagnostics systems to quantify a fault is of great importance as that would give an insight into the actual condition of the engine and the possibility of simulating the engine to understand the effects of such faults. Crucial decisions on the operational availability and maintenance could be made based on the life prediction model. This paper deals only with the creep life usage for life cycle management in a limited way. However, a more comprehensive system which includes various factors like cyclic fatigue, hot corrosion, environmental conditions etc. will have to be considered for more realistic analysis.

APPENDIX ‘A’

CREEP LIFE CALCULATION PROCEDURE

The life of the rotor blade can either be established by a manufacturer’s warranty for a particular operating condition and type of duty or by a minimum requirement. For the purpose of the analysis the HP rotor turbine blade life has been assumed to be 80,000 hrs for the Intercooled-Recuperated engine. Having ascertained the design point life the next step is to calculate the lives at various operating points. These require the use of Larson Miller Parameter (LMP) for which component stress and metal temperature are to be calculated. In addition the creep life usage would depend on the mission profile of the ship and therefore it is important to know the time spent at different power setting (for temperatures). The procedure is enumerated in below:-

(a) Stress Calculation. Stresses in rotor blades are basically caused due to centrifugal forces and due to gas bending forces. The total stress at any given time is the sum of the two forces. Since the centrifugal force is directly proportional to the rotational speed of the component, it follows that the stresses arising from such force will be directly proportional to the square of spool speed. Therefore the stresses arising due to the spool speed at any given time can be calculated using:

$$\frac{\sigma}{\sigma_{design}} = \left[\frac{N}{N_{design}}\right]^2 \qquad (1)$$

this can also be represented as:

$$\sigma = \sigma_{design} \times PCN^2 \qquad (2)$$

where,
σ = Stress
N = RPM
PCN = Spool speed relative to Design Point RPM

(b) Metal Temperature calculation.
Since the turbine blades are cooled, the metal temperature would be less than the gas temperature and would depend on the gas temperature around the component, coolant temperature at inlet and outlet of the component and mass flow of the coolant air into the component. Also the temperature will vary from point to point along the radial and transverse direction in the blade. It is therefore it is very difficult to obtain the true temperature at all points on the blade and it is reasonable to assume that the overall cooling effectiveness would remain constant and the following relation would hold good

$$\varepsilon = \frac{T_{gas} - T_{metal}}{T_{gas} - T_{coolant}} \qquad (3)$$

$$T_{metal} = T_{gas} - \varepsilon(T_{gas} - T_{coolant}) \qquad (4)$$

Cooling Effectiveness ε in its basic form is defined as:

$$\varepsilon = \frac{m^{*}\eta_c}{1 + m^{*}\eta_c} \tag{5}$$

(c) Creep life at a given temperature.

The next requirement is to calculate the time to rupture at a given temperature and it depends on the LMP and temperature. LMP depends on the temperature and stress and it is related to stress by the formula:

$$P = A_1(\log\sigma) + A_2(\log\sigma)^2 + A_3(\log\sigma)^3 + A_4(\log\sigma)^4 \tag{6}$$

The next step is to calculate the value of LMP at design point and it can be done using the design life and design point temperature. The values of constants from the creep rupture data are A_1= 18.4, A_2= 2.14, A_3= -2.32 and A_4= 0.27 for the WR21. Using the constant values the design point LMP and design stress are 26.54 and 31.02 KPas respectively for WR21 model.
(d) Creep damage determination.
The creep damage resulting from each time interval t , of applied stress is defined as the ratio of the time (T) to the time-to -rupture (TR). The creep damage is then defined as the summation over the cycle of the ratio t/tr. The portion of the total damage attributable to the creep t is then obtained by summing the damage for all the applied cycles. If the applied cycles are the same the summation reduces to n times the summation obtained for one cycle. Using Miners' Law which states that the cumulative creep life is the inverse of sum of the ratios of rupture time to time spent at that particular condition. Minor's law can be mathematically represented as:

$$\frac{1}{T} = \frac{T_{RA}}{T_A} + \frac{T_{RB}}{T_B} + \frac{T_{RC}}{T_C} + \cdots\cdots + \frac{T_{RN}}{T_N} \tag{7}$$

Therefore $$T = \frac{1}{\sum_{1}^{n} \frac{T_{RN}}{T_N}} \tag{8}$$

where

T is the cumulative life of the component
T_{RN} is the rupture life of component at condition N
T_N is the life component spends at condition N

REFERENCES

1. Hoeft,R. & Gebhardt, E. ,2000: Heavy duty gas turbine operating and maintenance considerations', GE Power leaders conference, Charlotte, North Carolina, 3-5 Apr 2000.
2. Singh,R. ,Zedda,M. and Gulati,A. 1999: "Advanced aircraft engine condition monitoring",Aircraft Technology Engine Yearbook 1999-2000.
3. Urban, L.A., Kos, J.M., and Perkins, M.L: "Multiple gas path analysis applied to a twin spool, mixed flow, variable geometry, turbofan engine", Report HSER 6794.

4. Goldberg David E "Genetic Algorithm: Search, Optimisation & Machine learning" ,Addison-Wesley Publishing Company ,Inc
5. Doel, D.L.,1993: “Gas path analysis – Problems and solutions”, Symposium of aircraft integrated monitoring systems, 21-23 Sep 1993, Bonn, Germany.
6. Doel, D. L., 1994: “An assessment of weighted least square based gas path analysis”, ASME 93-GT-119.
7. Sampath,S and Singh, R, 2004 : “An integrated fault diagnostics model using genetic algorithm and Neural networks”, Journal of Engineering for Gas Turbines & Power, ASME Publications pg 49-56 Jan 2006.
8. Spector R.B. ,1989, “A Method of Evaluating Life Cycle Costs of Industrial Gas Turbines”, ASME, Journal of Engineering for Gas Turbines and Power,1989.
9. Eustace, R., 1993: “Neural Network fault diagnosis of a turbofan engine”,XI ISABE 93-7091,Tokyo,Japan,September 19-24,pp937-946.
10. Torella, G. and Lombardo, G., 1995: “Utilization of neural networks for gas turbine engines”, Proceeding XII ISABE, pp. 358-366.
11. Illi, O.J., Greitzer, F.L., Kangas, L.J., 1994: “An artificial neural network system for diagnosing gas turbine engine fuel faults”, 48th Meeting Mechanical failures prevention group, Wakefield, MA, USA, 19-21 Apr 1994.
12. Zedda, M. and Singh,R.,1998: “ Fault diagnosis of a turbofan engine using neural networks: a quantitative approach”,34th Joint Propulsion Conference & Exibits,July 13-15,1998/cleaveland,OH
13. Gulati,A. , Zedda, M. and Singh,R: " Gas Turbine engine and Sensor multiple point analysis using optimisation techniques" AIAA/SAE/ASME/ASEE 36th Joint Propulsion Conference and Exhibit, July 2000, Alabama
14. Zedda, M. and Singh, R., 1999: “Gas turbine engine and sensor diagnostics”, IS10/UNK010, XIV International Symposium on Air-Breathing Engines (ISABE), 5-10 September, Florence, Italy.