GAS TURBINE PERFORMENCE BASED CREEP LIFE ESTIMATION USING SOFT COMPUTING TECHNIQUE

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ABSTRACT

Accurate and simple prediction system has become an urgent need in most disciplines. Having the accurate prediction system for gas turbine components will allow the user to produce reliable creep life prediction. Focusing on the turbine blades and its life, the current method to calculate its creep life is complex and consumes a lot of time. For this reason, the aim of this research is to use an alternative performance–based creep life estimation that is able to provide a quick solution and obtain accurate creep life prediction. By the use of an artificial neural network to predict creep life, a neural network architecture called Sensor Life Based (SLB) architecture that produces a direct mapping from gas path sensor to predict the blade creep life was created by using the gas turbine simulation performance software. The performance of gas turbine and the effects of multiple operations on the blade are studied. The result of the study is used to establish the input and output to train the Sensor Life Based network. The result shows that the Sensor Life-Based architecture is able to produce accurate creep life predictions yet performing rapid calculations. The result also shows that the accuracy of prediction depends on the way, how the gas path sensor is grouped together.

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LIST OF SYMBOLS AND ABBREVIATIONS

ANN - Artificial Neural Network
b - Bias
CL - Creep Life
CFD - Computational Fluid Dynamic
CT - Combustion Turbine
DT - Destructive Test
$E_{Abs,}$ - Absolute Prediction Error Percentage
f - Function
FB - Functional-Based
FF - Fuel Flow
HP - High Pressure
HCF - High Cycle Fatigue
LCF - Low Cycle Fatigue
L_{CMin} - Minimum Creep Life
LP - Low Pressure
MSE - Mean Squared Errors
MLP - Multilayer Perceptron
NDT - Non-Destructive Test
P3 - Compressor Outlet Total Pressure
P15 - Power Turbine Outlet Total Pressure
PCN - Relative Compressor Rotational Speed
R - Regressions
RB - Range-Based
SB - Sensor-Based
SLB - Sensor Life-Based

SP - Shaft Power

T_m - Metal Temperature

T3 - Compressor Outlet Total Temperature

T12 - Power Turbine Inlet Temperature

T15 - Power Turbine Outlet Total Temp

TET - Turbine Entry Temperature

TMF - Thermal-Mechanical Fatigue

W - Weight

Z - Targeted parameter

$z^{\wedge}$ - Output Parameter

σ - Applied Stress

UTHM - University Tun Hussein Onn Malaysia

Chapter 1

Introduction

1.1 Introduction to Gas Turbines

In the history of energy conversion, however, the gas turbine is relatively new. The first practical gas turbine used to generate electricity ran at Neuchatel, Switzerland in 1939, and was developed by the Brown Boveri Company. The first gas turbine powered airplane flight also took place in 1939 in Germany, using the gas turbine developed by Hans P. von Ohain. In England, the 1930s' invention and development of the aircraft gas turbine by Frank Whittle resulted in a similar British flight in 1941[1].

The name "gas turbine" is somewhat misleading, because to many it implies a turbine engine that uses gas as its fuel. Actually a gas turbine (as shown schematically in Figure1.1) has a compressor to draw in and compress gas (most usually air); a combustor (or burner) to add fuel to heat the compressed air; and a turbine to extract power from the hot air flow. The gas turbine is an internal combustion (IC) engine employing a continuous combustion process. This differs from the intermittent combustion occurring in Diesel and automotive IC engines.

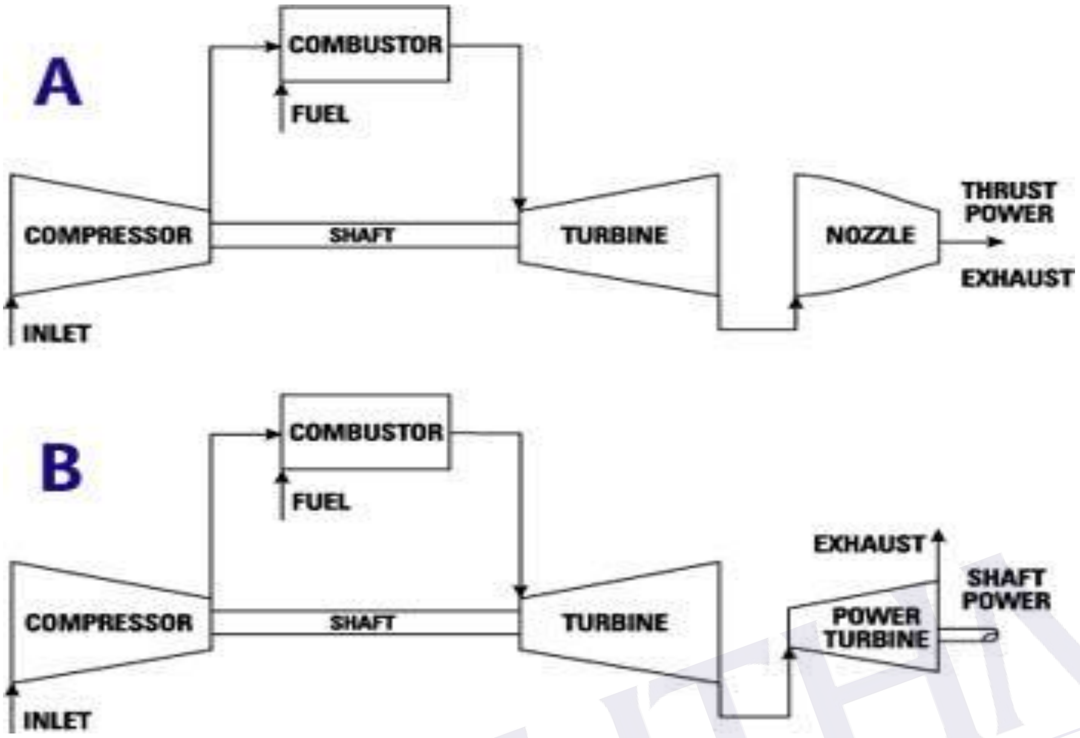

Figure 1.1: Schematic for a) an Aircraft Jet Engine; and b) a Land-Based Gas Turbine.[1]

Because the 1939 origin of the gas turbine lies simultaneously in the electric power field and in aviation, there have been a profusion of "other names" for the gas turbine. For electrical power generation and marine applications it is generally called a gas turbine, also a combustion turbine (CT), a turbo shaft engine, and sometimes a gas turbine engine. For aviation applications it is usually called a jet engine, and various other names depending on the particular engine configuration or application, such as: jet turbine engine; turbojet; turbofan; fanjet; and turboprop or prop jet (if it is used to drive a propeller). The compressor combustor- turbine part of the gas turbine is commonly termed the gas generator [1].

The advance of gas turbine engines and the increase in fuel efficiency over the past 50 years relies on the development of high temperature materials with the performance for the intended services. The cutaway view of an aero engine is shown in Figure1.2. During the service of an aero engine, a multitude of material damage such as foreign object damage, erosion, high cycle fatigue, low cycle fatigue, fretting, hot corrosion/oxidation, creep, and thermo mechanical fatigue will be induced to the components ranging from fan/compressor sections up front to high pressure (HP) and low pressure (LP) turbine sections at the rear.

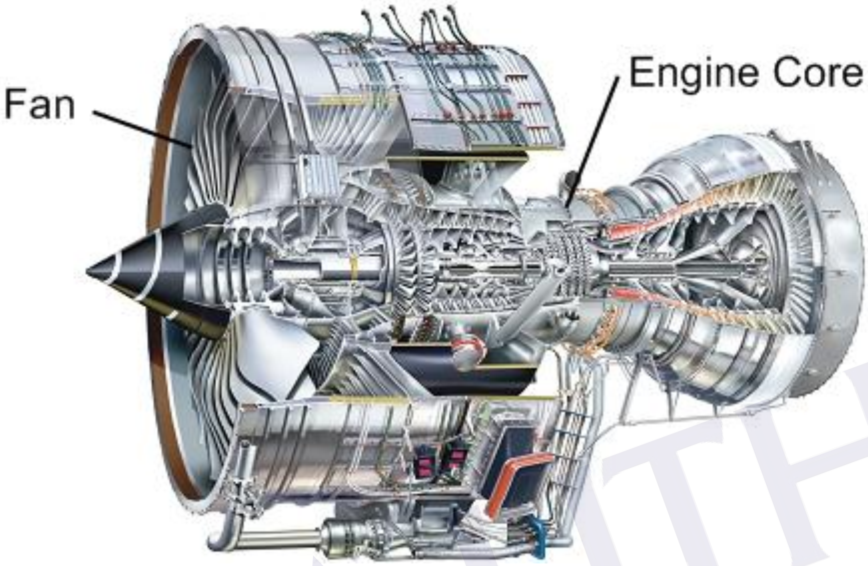

Figure1.2: Cutaway view of the Rolls-Royce Trent 900 Turbofan Engine. [2]

The endurance of the gas turbine engine to high temperature is particularly marked by the creep resistance of HP turbine blade alloy. Figure 3 shows the trend of firing temperature and turbine blade alloy capability[2]. Since 1950, turbine bucket material temperature capability has advanced approximately 850℉/472℃, approximately 20℉/10℃ per year. The importance of this increase can be appreciated by noting that an increase of 100℉/56℃ in turbine firing temperature can provide a corresponding increase of 8% to 13% in output and 2% to 4% improvement in simple-cycle efficiency. Advances in alloys and processing, while expensive and time-consuming, provide significant incentives through increased power density and improved efficiency.

The increases in bucket alloy temperature capability accounted for the majority of the firing temperature increase until the 1970s, when air cooling was introduced, which decoupled firing temperature from bucket metal temperature. Also, as the metal temperatures approached the 1600℉/870℃ range, hot corrosion of buckets became more life-limiting than strength until the introduction of protective coatings. During the 1980s, emphasis turned toward two major areas: improved processing to achieve greater bucket alloy capability without sacrificing alloy corrosion resistance; and advanced highly sophisticated air-cooling technology to achieve the firing temperature capability required for the new F generation of gas turbine. The use of steam cooling to further increase combined-cycle efficiencies will be realized in the 1990s [3].

The state-of-the-art turbine blade alloys are single crystal Ni-base super alloys, which are composed of intermetallic γ’ (Ni3Al) precipitates in a solution-strengthened γ matrix, solidified in the [100] crystallographic direction. Turbine disc alloys are also mostly polycrystalline Ni-base super alloys, produced by wrought or powder metallurgy processes. Compressor materials can range from steels to titanium alloys, depending on the cost or weight-saving concerns in land and aero applications. Coatings are often applied to offer additional protection from thermal, erosive and corrosive attacks. In general, the advances in gas turbine materials are often made through thermo mechanical treatments and/or compositional changes to suppress the failure modes found in previous services, since these materials inevitably incur service-induced degradation, given the hostile (hot and corrosive) operating environment.

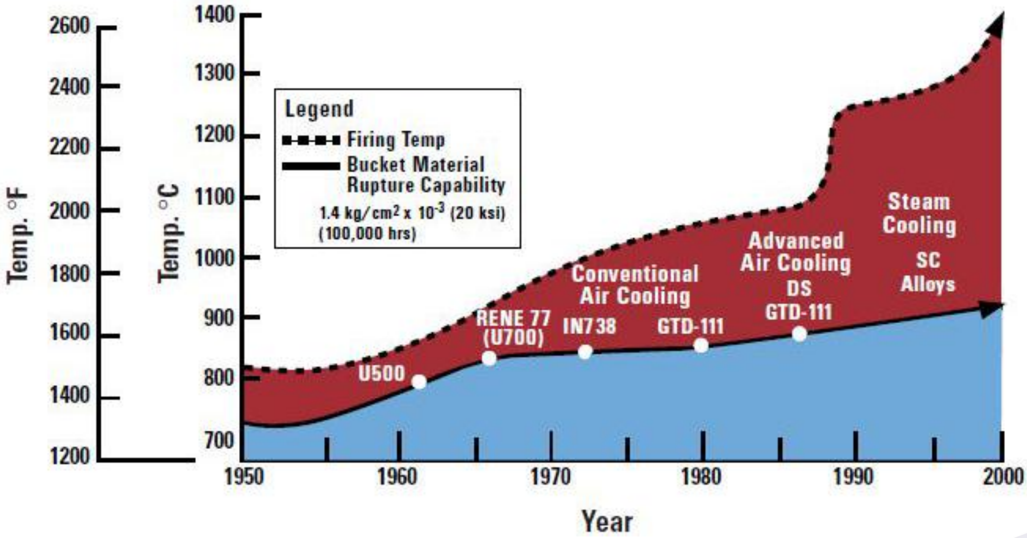

Figure1.3: Increase of Firing Temperature with Respect to Turbine Blade Alloys Development. [3]

Therefore, the potential failure mechanisms and lifetimes of gas turbine materials are of great concern to the designers, and the hot-section components are mostly considered to be critical components from either safety or maintenance points of view. Because of its importance, the methodology of life prediction has been under development for many decades. [3]

As the firing temperatures are increased and the operating cycles become more complicated, the traditional approaches are too costly and time-consuming to keep up with the fast pace of product turn-around for commercial competition. The challenges in life prediction for gas turbine components indeed arise due to their severe operating conditions:

- High mechanical loads and temperatures in a high-speed corrosive
- Erosive gaseous environment.
- The combination of thermo mechanical loads and a hostile environment may induce a multitude of material damages including low-cycle fatigue, creep, fretting and oxidation.

- Gas turbine designers need analytical methods to extrapolate the limited material.[2].

The attempt to signified the traditional process have been done by Abdul Ghafir[4] via soft computing technique to develop an alternative performance-based creep life estimation method that is able to provide a quick solution to creep life prediction while at the same time maintaining the achieved accuracy and reliability as that of the model-based method. Using an artificial neural network, the existing creep life prediction sub processes and secondary inputs are ‘absorbed’ into simple parallel computing units that are able to create direct mapping between various gas turbine operating and health conditions or gas path sensors and creep life. As his work has shown promising outcomes, it is the intention of this project to complete his work and look for any opportunity to improvement.

1.2 Problem Statement

In depth blade life estimation takes place in the design stage, current model-based creep life estimation methods have become more and more complicated and therefore demand huge amounts of work and significant amount of computational time [10, 11, 12,13]. For this reason, there are used to find an alternative solution that can reduce complexity of the estimation creep life, to be able to perform rapid computation and more accurate, also reduce the cost of design.

1.3 Project Objectives

Its measurable objectives are as follows:

a) To study the effects of different operating conditions on component creep life consumption for a selected turbine engine.

b) To construct an alternative neural-based creep life estimation model that enables a direct link between the gas turbine operating conditions and the components' corresponding life.

1.4 Project Scope

This project is primarily concerned with the creep life estimation, the scopes of this project are:

a) Creep deformation is only considered in the research component of the life assessment.
b) The component that's they studied is high pressure turbine blade.
c) ANN is used to construct the alternative creep life estimation model where the reduction of the complexity will be done at a macro level.
d) A turbo shaft engine performance model is used to show the application of the alternative creep life estimation method.

Chapter 2

LITERATURE REVIEW

2.1 Common Failure in the Gas Turbine Hot Section

The failure of metal parts is a complex phenomenon that depends on material, temperature, deformation, and the rate at which strain is applied. When a metal component breaks, two major questions need to be answered; what are the modes of the failure and what is the origin of the damage; hence examination of the 'how' is essential to understand the deterioration phenomena [4].

When gas turbine hot section components are being operated at extreme operating conditions, several damage mechanisms such as fatigue, high temperature corrosion/oxidation, and creep deformation will inevitably emerge. The presence of such mechanisms will cause the component to lose its ability to sustain its intended function, increase its life consumption rate, and to some extent, will cause the component to fail prematurely [4].

2.1.1 Fatigue

Fatigue, broadly speaking, is caused by repetitive loads that produce fluctuations in the components' stress, hence if large enough, will cause the component to fail even though the . Is much lower than that required for failure on single load application. Consequently, it will lead to crack initiation and propagation which ends with a fracture.

Fatigue, in this context, can be either mechanical or thermal-mechanical fatigue (TMF). Mechanical fatigue is a failure occurring under cyclic loading which is, for example, caused by vibration. on turbine blades during gas turbine start-stop cycle and power change. Mechanical fatigue can be further divided into two: high cycle fatigue (HCF), and low cycle fatigue (LCF). The distinction between them is where the repetitive application of load is taking place. HCF is categorised by high frequency and low amplitude elastic strain. An example of HCF will be when the turbine or the compressor blade is subjected to repeated bending, such as when the blade passes behind a stator vane, hence emerges into the gas path which will bend the blade due to high velocity gas pressure. This will force the blades to vibrate and the excitation at some point will match the blade's resonant frequency causing the amplitude of vibration to increase significantly LCF on the other hand is categorized by low frequency and high amplitude plastic strain. When dealing with LCF, the yield limit of the material is often exceeded and the material becomes plastic; therefore, repetitive plastic deformation is the main cause of LCF. Although there is no distinct border between the two types of failure, the traditional approach is to classify failures as HCF and those occurring below that value as LCF , TMF on the other hand occurs when the component is not only exposed to cyclic loads but is also experiencing variations in temperature gradient, resulting in significant thermal expansion and contraction. According to Jacobsson, turbine blade cooling which is used to lower the turbine blade's temperature will induce high temperature gradients between the blades high and cold regions thus generating σ, and during service, the effect of variation results in TMF [4]

2.1.2 High Temperature Corrosion/Oxidation

Both turbine and compressor are exposed to aggressive corrosive and oxidizing conditions that may be caused by several factors [14]:

a. Ingested air which contains sodium and chloride in the form of salt from the sea or from runaway de-icing treatment or marine environments.

b. Atmospheric contaminants resulting from pollutions from industry or forest fires which usually contain sulphur and sodium.

c. Volcanic activity which can generate significant levels of pollutants particularly sulphur.Gaseous combustion products which contain elements such as sulphur, vanadium or even lead and bromine from fuel at higher temperatures.

Although the blades have a protective coating, corrosive and oxidation attacks are unavoidable, especially when the blades are exposed to sufficiently contaminated surroundings or too much harmful fuel element [4].

2.1.3 Creep Deformation

Creep is a time dependent, thermally assisted deformation caused by prolonged high operating temperatures coupled with constant mechanical loading (below the yield stress of the material). Creep will cause the gas turbine hot section components to ‘stretch’ or elongate. Taking turbine blades for example, in the event of severe creep deformation, the physical shape of the blades will change and hence can no longer function properly. In addition, the elongation will cause the blades to be in contact with the casing, causing the blades to fracture and finally lead to engine failure. Figure 2.1 depicts several deformed turbine blades under creep attack. Note that the blades have already lost their original features at the tip, indicating a severe creep attack.

Figure 2.1: Deformed Turbine Blades Under Creep Attack. [4]

Although different materials have different strengths to resist creep deformation, it can generally be said that creep becomes significant when the homologous temperature (ratio between the material temperature and its melting temperature) is more than 0.5 but it can be in the range of 0.4 to 0.6.

2.2 CREEP LIFE ESTIMATION APPROACHES

When a hot section component is put into service and operates at a creep regime, its life will be consumed progressively as shown in Figure 2.2. This is due to the fact that both the deformation and fracture are becoming time-dependent. The rate of useful life consumption will depend on the ability of the material to resist creep deformation and also the gas turbine operating condition. The more volatile the operating condition, the faster the material will be degraded thus the quicker the useful life will be consumed.

As the material degrades progressively, micro-cracks will start to initiate on the surface and will propagate. According to Betten et al., the influence of micro-cracks on creep behavior begins even at the primary stage and the cracks become visible at the tertiary creep stage when the linkage of blunted micro-cracks into macro-crack occurs. The macro-cracks will propagate before the final creep fracture takes place [4].

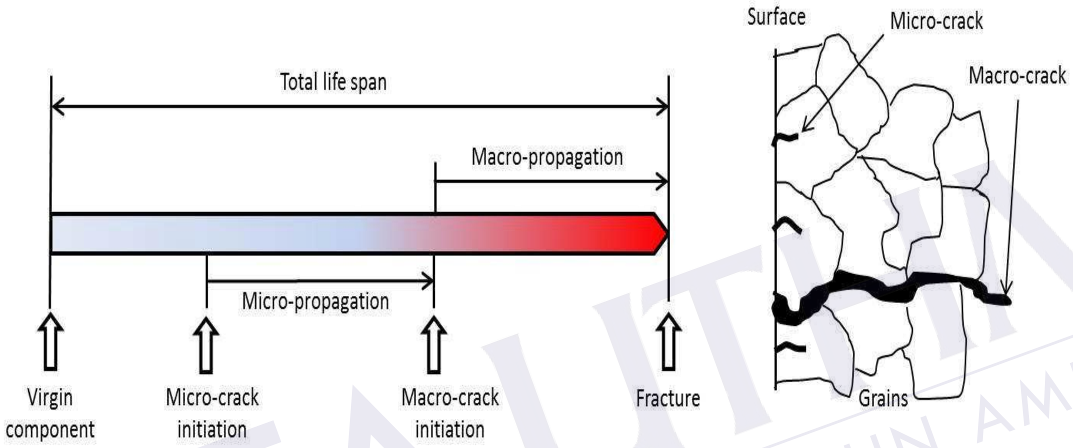

Figure 2.2: Life span of hot section component due to creep deformation. [4]

There are several methods for estimating creep life. In general, these methods can be classified into four broad approaches [4]:

a. Model-Based approach
b. Service-Based approach,
c. Statistical/Probabilistic-Based approach.
d. Soft Computing approach

It is important to note that in later sections of this thesis, some of the works related to the life estimation of turbine blades will be given for each approach. Nevertheless some works relating to the life estimation of other components are given as well.

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