Monitoring Material Degradation in Aircraft Turbine Blades: A Comprehensive Survey on Current Techniques

Joshua K. Ngoret and Venkata P. Kommula

Abstract**—**An aircraft turbine is the power harness of the engine. It however, operates under intense mechanical, extreme aerodynamic and severe temperature loading. The extremes of these environments renders turbine blade material to be vulnerable to attacks by: corrosion, erosion, oxidation, fretting, crack formation, crack propagation, creep, fatigue, or even microstructure damage. It is prudent to monitor degradation resulting from the above cited factors lest the long-term effect be grounding of aircrafts for unscheduled maintenance. Grounded aircrafts are a loss of revenue, yet again unplanned maintenance is an unplanned maintenance expense. This paper seeks, therefore, to analyze the modern methods used in the aviation industry for monitoring turbine blade material degradation. Literature on sampled techniques have been compiled and analyzed. Key approaches in the study range from; optical, microstructural change observations, metallurgical approaches, reliability testing, statistical methods, simulation, probabilistic algorithms and use of sensors. Identification of gaps in these techniques has been done. Impacts of the study range from informing of real-time degradation monitoring approaches, proposition of adoptable ones, from ease of learning, administering and teaching. Questions left unanswered by existing methods will form a debate platform for further research to increase accuracy and reliability in newer to be developed techniques.

Keywords**—** Material degradation, Turbine Blade, Probabilistic-Simulation Approach, Microstructural Approach, Reliability Approach , Algorithmic Approach

I. Introduction

THIS review paper acknowledges the work done by other researchers in monitoring turbine blade material degradation. It critiques strengths and weaknesses of the various approaches already undertaken in this field. The reader is, therefore, informed of advancements made in the idealization of solving turbine blade material degradation related problems.

A. Overview

In order to realize real-time and accurate material monitoring technologies, detecting, classifying, predicting and analyzing developing failures is crucial. Having these processes procedurally mapped can significantly assist to cut down on operating and maintenance costs while keeping track of the life of critical engine components [1, 2].

With a number of methods already in place; newer, smarter, time and cost effective ones are still remain to be of interest to researchers. The quest for more accurate, reliable or integrated approaches will give air-operators and manufacturers a wide selection of techniques to in-cooperate in their day to day material monitoring tacts.

B. IMPORTANCE

Appreciable work has been done in this field. Challenges are still well noted in many of the material monitoring techniques. Amongst them are fixation of surrounding operating environment conditions, lack of reliable data to follow through the monitoring process, changes in flight operating environment, no subjection of material to actual experimental or simulated conditions, proposed algorithms based on reliability with little as well as no relationship to real operating environment. Motivation in this work is to probe strengths and weaknesses of various currently used methods.

C. AIM

This paper surveys various approaches already in place to monitor turbine blade material degradation as well as identifying the gaps that still pose research questions for further investigation.

II. SURVEYED METHODS

A. 2.1 Advanced Diagnostics and Prognostics for Risk Assessment

Probabilistic-Simulation Approach based on directly sensed parameters from Engine Health Monitoring (EHM) systems, conducting checks in addition to making reference to historical reliability data for provision of inputs to predict failures [3].

Sensors are first identified and evaluated against their data to minimize the possibility of malfunction. A number of algorithm outputs are then combined with diagnostic fusion techniques to identify faults of EHM system. Probabilistic or physics-based models are preferred to obtain the prognostic

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projections taking into account design parameters and operating conditions [4].

Robustness of an EHM can further be enhanced by integrating fused sensor validation and recovery aids, anomaly detection and diagnosis of probabilities and stochastic classification of faulty vibration.

For validation and diagnostic of sensors the following two ways could be followed; signal processing based and physics-based. Signal processing techniques detect and diagnose sensor anomalies independent of a monitored system's characteristics. On the other hand, the physics-based model facilitates sensor recovery and virtually sensing parameters developed from prior knowledge of the system characteristics [5, 6].

A correlation matrix is then assigned to track real-time co-linearity between signals and detect errors [7] .

Within conditions for which a fault is known, stochastic models can be used to compute the remaining useful component life. Further still, a neural network or probabilistic-based autonomous system can be created for real-time failure prognostic predictions [8].

B. Modal Analysis, Campbell and Interference diagrams

Simulation-Statistical Approach that was used on a gas turbine that abruptly failed during morning start-up. Of 81 blades constituting the first row, only one blade was broken at its root. Investigations revealed that maximum stress on broken blade was reached due to development of the pressure profiles during operation [9].

Modal analysis was carried out to ascertain natural frequencies and modal shapes for fixed boundary conditions both experimentally and numerically. Campbell diagram and Interference diagram were then drawn to check the dynamic characteristics of the blades, while vibration was measured using accelerometers during the operating condition [10].

From the case studied above, resulting natural frequencies were not corresponding to heightening temperatures inside the combustion chambers, as the rotating condition could have changed the natural frequencies of the blade assembly.

It was particularly expected that the values of yield strength and Young's modulus to reduce with a rise in temperature for the test material, Inconel 738. However, from Campbell diagram, there was a shift in natural frequencies suggesting dependency of frequency on the operating temperature. Similarly, since Campbell diagram was drawn for only one blade with fixed boundary condition, natural frequencies for the entire assembly and the nodal diameter of the assembled blades could have been more informative [9, 11] .

C. Health Monitoring and Prognostics of Blades and Disks with Blade Tip Sensors

Microstructural-Algorithmic Based Approach. In this technique blade tip sensors are embedded in engine casing to monitor blade tip clearance and vibration. Sensor technologies range from the use of capacitors, inductors, microwave signals, infrared, eddy-currents, pressure transducers, acoustic sensors, magnetic signals among others.

From tip sensors, crack growth is evident from blade lengthening over time accompanied by loss of protective coating due to wear or centrifugal force affecting blades directly above the crack. Signal indicating the fault is then isolated and distinction carried out using data reduction differentiators [12-18].

In specific reference to application of capacitive sensors for example, heavy duty probes, high frequency signal outputer, signal amplifier and a processor constitute a unit assemblage. Each blade is exposed under extreme predetermined temperature and severe conditions, where signal measurements carried out. Processing of signals then follows by sophisticatedly integrated electronic circuits. Quantities such as vibration, eccentricity, rotational anomalies can then be calculated [19].

D. Microstructural Study

The method evaluates microstructural change on the turbine blades after exposure to service to reveal systematic developing changes. The aim being to establish engine operating conditions. Against designers and manufacturers preset standards for permissible limits to degradation can be gauged. Microstructural study complements metallographic analysis, which in atleast one of their procedural implementation are optically carried out [20, 21].

Important to note is microstructural changes of materials for the blades is informed by alloying system and engine operating conditions which are prefixed by the engine manufacturers [1, 4, 22, 23].

E. Health Risk Assessment and Prognosis of Gas Turbine Blades by Simulation and Statistical Methods

Simulation-Statistical Approach that utilizes Monte Carlo Simulations of operational data for blade health assessment and prediction of future usage. The method works by algorithm formulation, application of data to be used then selection of Blade Tooth Clearance (BTC) criterion. Two probabilistic distributions (lognormal and normal) of blade tip clearance data with life usage are plotted failure risk assessment from sensor data. A regression analysis for turbine blade life prognosis is then carried out [1, 3, 24-26].

Extremum Selection Method (ESM) is an example of such a mathematical model for nonlinear reliability analysis. The model having been tested for radial deformation of gas turbine blades yielded results of accuracy of upto 99.972% [27].

F. Optical Methods

Microstructural Observation Approach. It includes: Visual, Metallographic scans, use of SEM, Quantitative examination of the base alloy, X-ray diffraction (XDR) examinations for Microstructure, Microprobe analysis, Deposit Analysis and Examination of laboratory specimens [28-33]. An example of damages that could be monitored using this technique is hot corrosion with characteristic microstructural changes by attacks of deposition of alkali metal sulfates on the blade or vane [4, 5, 7]. Fuels usually have contaminants such as; sulfur, sodium, potassium, vanadium, lead, and molybdenum which form erosive or corrosive compounds on blade surface in a number of ways such as:

(i) Mechanical disruption of the blade oxide coating by erosion, thermal cycling and or elastic strain of the substrate putting the oxide coating on the blades under tension [8]
(ii) Diffusion of sulfur through the oxide until chromium-rich sulfides form within the metal [9, 11]
(iii) Dissolution of the protective oxides by salts [19, 34]
(iv) Local reducing environment [35]

G. Component Diagnostic & Prognostic Modeling

Simulation-Probabilistic Approach. The technique works by evaluating the distribution of remaining useful component life against uncertainties in component's condition for a particular fault. Collected data, diagnostic results, current condition assessment data and operational profile are then used to create a neural network or probabilistic-based autonomous system for real-time failure prognostic predictions [18].

From the output, damage occurring to a material piece can then be considered for two actions. A corrective one, to repair or replace the part, or a compensatory one to lower the systems' operational loads in order to extend the life of the faulted part [1, 18, 32, 36-46].

Common examples of methods employed in Component Diagnostic & Prognostic Modeling are:

(i) Gas Path Analysis (GPA)

GPA is a physical model capable of acquiring, processing measured data and relate with health parameters as well as assign a decision making process. A GPA for example, can represent the aero-thermodynamic processes occurring in engine components with mechanical coupling linking them to a mathematical model in a black box that relates measured signals with health parameters. The resulting decision making process may then either be a specified pattern recognition technique or an artificial intelligence based expert system. The models are classified according to their constituent elements as being: Steady or Transient in states, Mathematical or Physical based, Artificial intelligence or Conventional methods [47].

(ii) Expert systems

Expert systems (ES) make use of expert knowledge from automated inference engines from computer programs to provide solutions to problems. Solutions from ES for engine diagnostics could be; rule, case, or model-based. Practically, specific expert knowledge from condition monitoring is never fully known, solutions are therefore also often inaccurate. For this reason, measures for undisclosed information and solution formulation is required for ES to be more robust in solving problems [47].

(iii) Hybrid and fusion information techniques

These are Genetic Algorithm and Artificial Neural Network integrated fault diagnostic models for identifying shifts in component performance and sensor faults [48]. The models operate in two categorical cases. Case one is use of response surfaces to compute objective functions aimed at improving exploration potential associated with a fault, thereby, easing computational burden. Case two applies concepts of neural network with genetic algorithm to create a hybrid diagnostics model. The neural network in this stage serves as a pre-processor to bring to minimum the number of fault groups to be investigated by the genetic algorithm based model. The results are improved accuracy, reliability and consistency as well as total run time [49].

H. Monitoring Low Cycle Fatigue (LCF) damage in turbine blade using vibration characteristics

Simulation- Reliability Approach. The approach works by rotation of Timoshenko twist beam with taper to model a turbine blade. Frequency data is generated from finite element analysis. An experimental model is subjected to continuum damage mechanics and non-linear nature of LCF is captured [50]. With LCF is known to cause significant material degradation that resulting in stiffness loss as the damage grows, this growth changes the rotating frequency of the model. Simulation deterioration curves of frequencies against damage are drawn to determine frequency thresholds at the point where 90% percent of blade life is damaged before ultimate failure [40, 44, 45, 51-53].

I. New Chirp-Wigner Higher Order Spectra (CWHOS) for transient signals with any known nonlinear frequency variation

Algorithmic Based Approach for nonlinearity detection of transient signals with nonlinear polynomial time variation of instantaneous frequency based on the Fourier transform, suggests Gelman et. Al [54]. System's input data is obtained from independent synchronous measurements of frequency sensors and tachometers. Two great challenges however, associated with the technique are; estimation of amplitude of signals with known time variation of the instantaneous frequency as well as the method entirely being restricted to work with stationary HOS, leaving out the non-stationary aspect [51, 55, 56].

J. Adaptive diagnosis of the bilinear mechanical systems

Statistical-Simulation Approach for diagnosis of bilinear mechanical systems by varying of resonance frequency from free oscillations.

Roemer et. Al [1] suggest that two paths of signal occurrence could result. Occurrence of frequency-independent and the frequency-dependent internal damping. Numerical simulation is conducted to determine the effectiveness of path to be adopted for computation of a component's accumulated damage [55, 57-62].

K. Non-Linear Vibro-Acoustical Free Oscillation

Vibro-Acoustal Approach based on excitation of oscillation free specimen. Processing of vibro-acoustical signals from specimen with oscillations is equally done with specimens having varying appearances of cracks. Decrease in free oscillations between these two specimens indicates crack occurrence, deduce Bovsunovsky and Surace [8].

Oscillations decrement depend on; crack size, damping factor with and without crack, as well as model's natural frequency. Analyses of decrement from the factors mentioned above is carried out for frequency-dependent and frequency-independent external and internal friction forces.

Validation of adapted method relies on the estimated value of natural frequency and interfering parameter. Results are then compared with theoretical prognosis obtained from nonlinear models [63-68].

L. Higher Order Coherences for fatigue crack detection

Vibration Based Approach designed to detect fatigue crack from the vibration responses of induced known excitation, natural excitation from rotating speed of machines or wind excited structures [69]. With information that when cracking occurs in structures, high harmonics on vibration are generated and that exciting frequencies accompanying are as close to natural frequencies as possible, coherence behavior can be formulated.

Bispectrum and Tricoherence are classical examples of such methods. They are designed to take into account double and triple Fourier Transformation of third and fourth order moment of time signals associated with two and three frequency components respectively [70].

Practical application of the cited methods, however, reveal that HOCs are calculated only for the exciting frequency and its related harmonics. This is because breathing of the cracks generate harmonics in the exciting frequencies saving computational effort and time without losing any information related to the crack detection process [59, 71-74].

Table I provides a summary of the sampled methods.

TABLE I: SUMMARY OF SAMPLED METHODS

Technique	Limitations	Surveyed Papers	Remarks
1. Advanced Diagnostics and Prognostics for Risk Assessment	a. No experimental or evidence of material degradation taken into account b. No loading was done on the blades	[3-8]	Probabilistic-Simulation Approach
2. Modal Analysis, Campbell and Interference diagrams	a. Natural Frequencies were inaccurate necessitating formulation of assumptions b. Speed of rotation was limited to 3600 rpm c. Nodal diameters of blades were overlooked d. Combustion process was ignored e. No loading was applied on the blades	[9-11]	Simulation-Statistical Approach
3. Health Monitoring and Prognostics of Blades and Disks with Blade Tip Sensors	a. Material damage was not taken into account b. Signal discrimination during interpretation can occur c. Differentiating amongst time dependent phenomena require refining of data and signal interpretation d. Heating process defines type of crack	[12-19]	Microstructural-Algorithmic Based Approach
4. Microstructural Study	a. Cumbersome, Time wasting, costly as the techniques require dismantling and assembling of the engine b. Methods assume microstructural changes are a result of alloying system and engine operating conditions alone c. One metallographic sample is not sufficient to explain degradation for a set of blades	[1, 4, 20-23]	Microstructural Observation
5. Health Risk Assessment and Prognosis of Gas Turbine Blades by Simulation and Statistical Methods	a. Data variation may arise in aircrafts from the same fleet but flying in different skies b. Faults were statistically computed c. Material damage was not taken into account d. No loading was applied on the blades	[1, 3, 24-27]	Simulation-Statistical Approach
6. Optical Methods	a. Cumbersome, Time wasting, costly and Highly trained personnel required to dismantle and assemble the engine b. No statistical data c. No formulated algorithms d. No blade loading conditions are considered, meanwhile the method focuses on material damage e. There is no quantification of damage	[4, 5, 7-9, 11, 19, 28-35]	Microstructural Observation
7. Component Diagnostic & Prognostic Modeling	a. Material degradation not taken into account b. No blade loading conditions are considered	[1, 18, 32, 36-49]	Simulation-Pobabilistic Approach

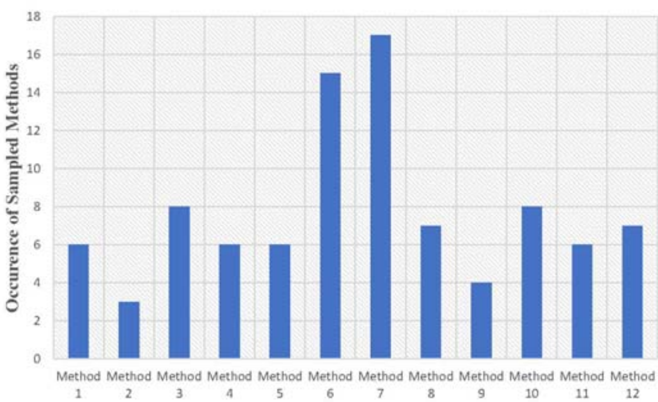
8. Monitoring Low Cycle Fatigue (LCF) damage in turbine blade using vibration characteristics	a. Material degradation not taken into account b. No blade loading conditions are considered	[40, 44, 45, 50-53]	Simulation- Reliability Approach
9. The New Chirp-Wigner Higher Order Spectra (CWHOS) for transient signals with any known nonlinear frequency variation	a. Material degradation not taken into account b. No blade loading conditions are considered c. Estimation of amplitude of signals with known time variation of the instantaneous frequency is difficult and also the method also entirely works with stationary HOS, leaving out the non-stationary aspect d. The method also entirely works with stationary HOS, leaving out the non-stationary aspect	[51, 54-56]	Algorithmic Based Approach
10. Adaptive diagnosis of the bilinear mechanical systems	a. Material degradation not taken into account b. No blade loading conditions are considered	[1, 55, 57-62]	Statistical-Simulation Approach
11. Non-Linear Vibro-Acoustical Free Oscillation	a. Material degradation not taken into account b. No blade loading conditions are considered	[63-68]	Vibro-Acoustal Approach
12. Higher Order Coherences for fatigue crack detection	a. Material degradation not taken into account b. No blade loading conditions are considered c. HOCs are calculated only for the exciting frequency overlooking related harmonics	[59, 69-74]	Vibration Based Approach

III. OBSERVATIONS & FINDINGS

In this paper a total of 74 articles have been reviewed, published between years the years 2000-2015. They form a valuable basis on which need for which open ended questions could further be developed for further research in the area of turbine material degradation.

The methods used for the study of blade material degradation monitoring are: Probabilistic Simulation Approach, Microstructural Observation, Reliability Based Approach, Vibration-Simulation Approach, Algorithmic Based Approach, Statistical, Simulation Approach, Vibro-Acoustal Approach, and Vibration Based Approach (See Table I).

Figure I: Popularity of Sampled Methods



From the reviewed approaches, the most popular approach was found to be Method 7, Component Diagnostic & Prognostic Modeling based approaches as shown in Figure I.

However, being a Simulation-Reliability Based Approach the shortcomings identified with this method are:

a. No blade loading conditions are considered
b. There is no quantification of material damage

It is a static based technique.

IV. CONCLUSION

The literature guide comprehensively looked at the various methods used in monitoring material degradation in turbine blades. Critique of each method has been done (See Table I).

Development of approaches that override the shortcomings of the reviewed methods will offer; real time, more accurate, time and cost saving, reliable, ease of administering and monitoring without compromising on safety and availability of the aircrafts for service.

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