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Monitoring the rotor blade arrival timings in aircraft engine using fiber optic sensors

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ABSTRACT

The rotor blades in aircraft engine accounts to forty two percent (42%) of the failures in gas turbines. There is a need for the unified treatment of their causes, failure modes and trouble shooting. A common failure of gas turbine is High Cycle Fatigue(HCF) of compressor and turbine blades due to high dynamic stress caused by blade vibration and resonance within the operating range of frequency. Studies and investigations on the failure of rotor blades are continuing since last five decades. High cycle fatigue is an arduous concern in rotating machinery especially to rotor blades which operate at high rotational speeds in harsh pressure and thermal environment. Estimation and evaluation of HCF contingencies depend heavily on tests and measurement techniques employed which has a high relevance in providing the mechanical integrity. Among the various experimental evaluations techniques used for blade vibration, monitoring the rotor blade arrival timings using fiber laser sensors is a unique non-contact measurement technique which provides detailed information related to the structural dynamics of all blades in a stage, in real time followed by offline analysis.

Keywords: Blade Tip Timings, BTT, High Cycle Fatigue, HCF, Non Intrusive Stress Measurement System, NSMS etc.,

Nomenclature

BAT	-	Blade Arrival Timing
HCF	-	High Cycle Fatigue
BTT	-	Blade Tip Timings
NSMS	-	Non-intrusive Stress Measurement System
TOA	-	Time Of Arrival
PWIG	-	Propulsion Instrumentation Working Group
OPR	-	Once Per Revolution
FEA	-	Field Elemental Analysis

I.INTRODUCTION

High Cycle Fatigue (HCF) in rotor blades of turbo machinery offers a unique challenge to the gas turbine designers across the industry, via, Military, Civil and Industrial power plants and its mitigation is highly arduous. Quantification of blade vibration in an operational environment is vital to assess the structural reliability with the test data component life can be estimated. In the early design phase, Finite Element Analysis (FEA) is utilized to estimate the modal parameters, which will be validated using strain gauges in the bench, rig, spin pit and engine tests. Acquiring the strain data through the complex slip rings or radio telemetry from the rotating structures is not only laborious and expensive but also results in high mortality of gauges. In addition, the strain gauges fixed over the small final compressor stage blade alter the modal characteristics substantially due to the considerable addition of mass and stiffness. An alternative method to assess the rotor blade vibration issue is the measurement of Blade Arrival Timings (BAT) in the aircraft engine using fibre laser sensors. This method provides a most compromising solution close to the strain gauges, which is considered as the industry standard for evaluating the structural response of blades and other components. This method is also known as Non-contact Structural Monitoring system or Non-intrusive stress measurement system (NSMS). It is evolving as a universal choice[1].

The leading group of instrumentation experts from all the US major gas turbine OEM's devoted large attention toward BAT and actively pursuing a framework for its implementation in-services engines. At present all the major engine houses such as Rolls-Royce, Pratt and Whitney, General Electric, MTU, SNECMA, Alstom, Siemens, Williams International and others are having dedicated in house research groups and evaluating the various elements of BAT, to attain sufficient maturity. Apart from the industry efforts, a few well known team of experts from Hood Technology Corporation, USA[2]. Agilis Measurement systems, USA[3], Roto Data, UK, QinetiQ,UK and others are also developing commercial systems.

This method, which measures the rotor blade vibration through and array of casing mounted sensors, accurately clocking each blade's time of arrival (TOA) using the measured blade deflection.

A. Reasons causing HCF

Fatigue is the weakening of the material caused by repeatedly applied loads. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading[6]. The largest single cause of component failures in modern military aircraft gas turbine engines is high cycle fatigue (HCF), exceeding the number attributed to low cycle fatigue, corrosion, overstress, manufacturing processes, mechanical damage, and materials. The HCF problem is a pervasive one, affecting all engine sections and a wide range of materials. In addition to the impact on engine component reliability, HCF problems cause significant economic impacts through field inspection and maintenance actions, and reduced readiness reliability.

There are several distinctly different sources of HCF damage in turbine engines, which can be generally classified as follows[10]

• Aerodynamic excitation - caused by engine flow path pressure perturbations, affecting primarily blades and vanes.

• Mechanical vibration - caused by rotor imbalance which affects external components, plumbing, and static structures; and rub, affecting blade tips and gas path seals;.

• Airfoil flutter - caused by aeromechanical instability, affecting blades.

• Acoustic fatigue - affecting mostly sheet metal components in the combustor, nozzle and augmentor.

The figure 1.1 and figure 1.2 clearly tells us the statistics of the failure of gas turbine engines due to several factors. Among all the factors, the failure caused by the blades of the engine system and the high cycle fatigue is at the top. So it is important to monitor the rotor blades of the aircraft engine system.

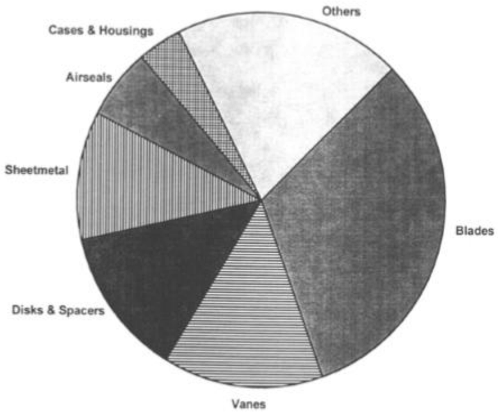

Fig 1.1 Representative distribution of HCF problem by components

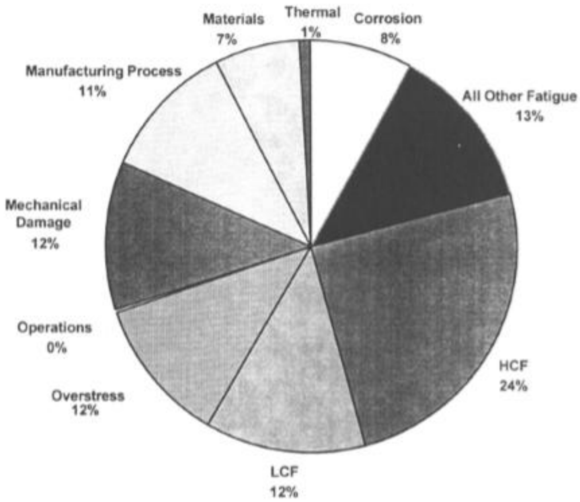

Fig 1.2 Representative gas turbine component distress mode statistics

B. History and the Development ofNSMS

NSMS technology was patented as early as 1949, with many improvements patented since that date. Some recent US practitioners believe that NSMS was first developed in 1980, by major aircraft engine OEMs (and the

US Air Force). It may be envisioned as a replacement technology to rotating strain gauges however it is currently used as an essential complement to strain gauges. The technology is widely used for turbo-machinery development and high cycle fatigue (HCF) troubleshooting. Due to the direct blade observation, external mounting and inherent serviceability of the sensors, NSMS has been used since at least 2006 as a long term health monitoring method.More recently, multiple practitioners are becoming active in this application of the technology[2].

•1st generation system – monitoring blade deflection only with a single probe and no computer processing, analog signal, no algorithms for stress

•2nd generation system – determining frequencies and the mode shapes, with the use of computers and more than one sensor, algorithms for frequency and modes sensor, algorithms for frequency and modes .

•3rd generation system – determining frequencies, mode shapes of single mode, typical 4 to 5 sensor per stage, on line monitoring of multi – mode integral orders, measurement threshold.

•4thgeneration –determining frequencies, mode shapes and stress, industry standard hardware and software, measurement threshold, Meas's stress a long span of blade with minimal penetration of gas path.

•5thgeneration –increased sensor resolution as well as real time, simultaneous vibration monitoring of several rotor stages

II. PRINCIPLE AND SYSTEM ARCHITECTURE

A. Principle

As elucidated earlier, Blade arrival timing is a non-intrusive measurement technique to measure the blade tip deflection, it works based on the bookkeeping of accurate blade arrival times with reference to a stationary reference. As explained in Fig 2.1 every non vibrating blade is expected to arrive at the sensor mounted in the engine case in an estimated time, proportional to the rotational speed. If the same blade vibrates or deflects then it arrives earlier or delayed depending on the amplitude and mode of vibration for a given sensor at a given rotational speed. Technically, the difference in the time of arrival (TOA) between the vibrating and non-vibrating blade position is accounted as the blade vibration amplitude.

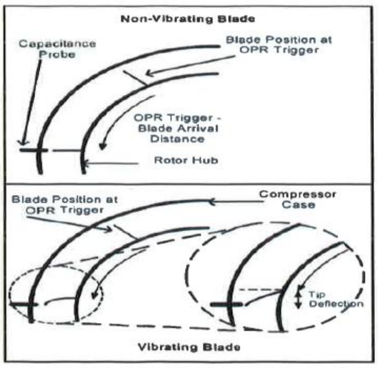

Fig 2.1 Arrival time of Non vibrating and vibrating blade

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While the spinning blade crosses the sensors measurement field as given in, corresponding voltage is produced proportional to its proximity and time of arrival.

Blade Deflection = Estimated time of arrival – Actual time of arrival

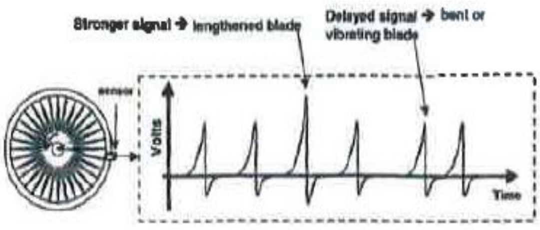

Fig 2.2 Signal train illustrating length and vibrating blade

B. System Architecture

The BTT system consists of the similar architecture for any type of sensor, where the sensors and its related components are chosen as per the functional requirement. In general, it consists of (i) sensor – could be eddy current, optical, capacitance, microwave/ radar, pressure- based, etc (ii) Amplifier / Modulator or light emitter and detector, depending on the type (iii) High resolution timer clock circuits (iv) computer with bespoke software for real-time and off-line analysis, and (v) once-per-revolution(OPR) sensor. The details about the sensors and their construction with relative merits and demerits are discussed in a separate section. A typical BTT system is given in Fig3, [7] however the figure explains the optical sensor based system with an eddy current sensor for speed measurement. In every type of BTT systems, the arrival of the blade is identified by the change in voltage/current depending on the type of sensor, which is conditioned by the amplifier unit placed closed to the test engine. The digitized signal is then converted to a pulse with a trigger value against the threshold value to mark arrival of the blade which is considered as an event with distinct time stamp.

Based on the measured engine speed using OPR and number of blades in the stage, the expected time of arrival, TOA is estimated whereas the blade pulse gives the actual TOA. To capture the infinitesimal time variation in the blade arrival, the present system timer clocks are having a timing resolution in the range of 80-200 MHZ with 5-12 ns (nano seconds) to cater for a spatial resolution of 1.6μm to 4 μm, in terms of tip deflection. The blade rim speeds up to 500ms-1 can be measured by the present tip timing systems, [2][3] Most of the OEM's configure their own whereas the equipment supplier customizes the sensor and system according to the hardware to be tested. Detailed information about the off-the-shelf systems are available from their respective websites and every system has an unique operational competitiveness over the others. Moreover the sensors have cross compatibility across the manufactures, since the fundamental principle of measurement remains the same and a trigger pulse is used for estimating the TOA.

On acquisition of the data in an industrial PC, bespoke software's using various analysis algorithms are available to infer the blade frequency, amplitude, damping and the type of vibration i.e Synchronous or Asynchronous. Conventionally, the systems can provide the fundamental synchronous and asynchronous data

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including tip clearance in real time. The offline analysis can generate a host of information such as nodal diameter, engine order, Campbell diagram, etc. the details related to the data processing algorithms are provided in a separate section. Heath et al [7] provides a comprehensive comparison of all the basic algorithms.

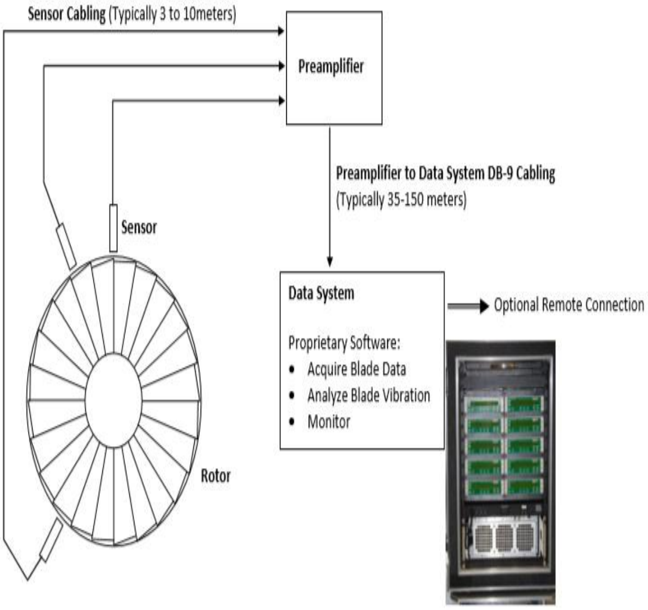

Fig 2.3 system architecture

III. COMPONENTS USED

Optical sensors has the good resolution, high bandwidth (30 MHZ) and fine spot size to capture the arrival of even thin blade tips. These sensors have two parts: the LASER light emitter through a fiber optic cable of typical diameter of 100µm in center surrounded by the other part, photo sensor, which takes the reflected light from blade tips. These sensors can produce measurement spot size as low as 200µm and can be combined with the lenses to focus on the specific blade location, from a distance.These sensors can be operated up to very high temperatures as claimed by hood tech USA. The sensors can be used up to 650 c without cooling and 1050c with air cooling and similar specifications are available with other too.

IV. BTT DATA ANALYSIS METHODS

Several analytical models and alogorithms are found in the literature to analyze the tip timing data, but the fundamental illustration is provided in [7] and few other rigorous theoretical ones are reported in literature [11][15]. The analysis method involves advanced curve fitting techniques taking into consideration the higher order complexity of the mode. The vibration analysis can be always classified under the synchronous and asynchronous categories with relevance to either a single blade or the completed blade disk. When compared against the experimental observations, many authors as in [16][17][18]& [19], found that the single blade analysis typically demonstrates a good correlation between the measured BTT data and strain gages. The outcome using these analysis algorithms and correlations are presented in section 5.0 and 6.0.

V. TYPICAL BTT OUTPUTS

The acquired data from any conventional test is subjected to rigorous analysis using the above mentioned methods combined with standard signal processing techniques to extract the relevant blade modal parameters. In the case of conventional measurements, the strain data is limited to a single blade whereas the tip timing includes the data for all blades in the stage. Among the various parameters evaluated using BTT data, the prominent ones are synchronous and synchronous responses, blade untwist or stagger, blade position or lean, blade tip clearance, etc. typical outputs of these analyses are presented below in comparison against test data.

A. Synchronous blade response

Based on the data collected by the fixed spatial variable sensors mounted in the casing, the individual blade response for all the blades can be estimated. The Fig 4.[2] below elucidates the resonance of a single blade estimated through the curve fit technique by the group of casing mounted sensors. This also explains the relevance of use of these algorithms for all individual blades in a stage. Apart from this the following synchronous outputs can be generated.

Individual blade modal parameters – frequency, amplitude, damping, etc. Fig 5.0 [18] gives the resonance of blade measured by different sensors located in the circumference of the casing. Overall blade response, an aggregate of all blades response indicates the system response and duration. This will be highly useful to calculate the HCF life of all the blades in a stage. Campbell diagram for the stage with all the resonant cross overs. Mistuning – the variation of blade frequency due to manufacturing tolerances. Duration of dwell in a particular mode for the given order of excitation, highly useful for HCF prediction.

B. Asynchronous blade response

As explained in the previous section, the ‘All blade spectra algorithm is powerful enough to predict the non-integral blade vibrations such as flutter, stall, surge, etc excited by aeroelastic force. Fig.6[18] below elucidates the statistical variation of all the blade response measured by BTT sensors during the flutter in the first torsion mode of vibration. Another Fig.7 from MTU[18], explains the ability of sensors to capture the surge events which is simultaneously measured using strain gauges.

C. Blade Resonance Tracking:

Using the blade characteristics in similar lines, the blade resonance can also be tracked in both real time and offline mode, to identify the possibility of distress in an engine. The occurrence of blade resonance is tracked using the non-contact measurement, however in the event of a blade crack the resonance band will shift considerably, to indicate the distress. This can be easily implemented for larger blades, whereas the spatial resolution and accuracy of blade position retards the use for rear stage blades. A illustration of this is provided by Ziller at al in [17].

D. Blade position identification

Blade stagger in assembly vary due to the manufacturing tolerances and result in a unique inter blade spacing and also constitute for the mistuning of the blade-disc. Using the discrete sensor locations around the casing as given in Fig.8 in [17], can be measure the exact blade position at any rotational speed and it is expected to be constant, if free from cracks. This feature is exploited to monitor the integrity of the blades in real-time, any drift in TOA at the given RPM, could indicate the failure of blade or disc. This is an extremely emerging powerful tool for the prognostics and diagnostics of blade and disc in-service, which is seriously considered by the industrial and research communities.

E. Blade untwist or stagger measurement

Another unique output from the BTT system which complements the aerodynamic designer to improve the design with better performance. Using two sensors along blade chord can track the movement in the leading or trailing edge with reference to a stationary reference. This will lead to the quantification of blade tip untwist or otherwise the stagger variation due to the centrifugal and aerodynamic forces at various flight conditions. This provision is available in commercial NSMS systems from Ms.Hood Tech and Ms.Agilis and published by engine house such as MTU as reported in [17].

F. Blade tip clearance measurement

Even though, blade clearances are measured in every engine test as a performance parameter using capacitance, eddy current or microwave sensors, the combination of it with tip timing leverages the utility of the test. This is an option which is highly pursued across the industry due to its versatility and ease in implementation as the hardware/sensor remains the same. Early work has been carried out in Cranfield University [4] to explore the possibility of the dual use of capacitance sensors in Aero engines and the similar effort is reported from NASA using Microwave sensors in [12]

VI. CORRELATION WITH THEORETICAL PREDICTIONS AND STRAIN GUAGES

Blade discs are modelled using a number of approaches, from Single Degree of Freedom (SDOF) system to complex Multi Degree of freedom (MDOF) including various damping models for characteristics and response predictions[21]. Apart from this rigorous fundamental approaches, FE predictions are considered as industry standard for comparing against the full field measurements to get insight into the dynamics and extrapolate the data for life prediction of components. Numerous references are available on this aspect, however references [4][16][17][20] provides firsthand account about the comparision of blade response models with test data.One
of the prime advantages of BTT systems over strain gauges is its ability to capture the response of all blades in real time followed by a detailed offline analysis using bespoke software. As given in [4], after estimating the modal parameters using FE analysis, the blade frequency and mode shape is verified using Electron Speckle Pattern Interferometer (ESPI) in a bench test. The same is verified in Low Speed Compressor rig set up as shown in Fig.10 from [4] and compared against the BTT data. Good correlation is observed between the FE prediction, bench test, strain results and BTT data.

The reliability of BTT systems are well established through the compressor rig testing carried out at MTU, in the presence of strain gages. The results of tip timing were compared against the strain gauges. The results of tip timing were compared against the strain gages, which are limited to a few blades in the stage, for the fundamental modes against various engine orders. The tip timing data is able to capture the response of all the blades and correlated well with the strain amplitude as given in Fig.11[18]

Another rig validation from US, Airforce, as given in [20] presented in IIS, 2012, PWIG[1], demonstrates the capability of NSMS system in terms of measuring frequency, deflection and inferred stress, using FEA for 36 blade test rotor in 7EO in first fundamental mode. The validation includes generating an experimental Campbell diagram using NSMS data and strain gage. The details are in the given figures.12,13 & 14 from the report [20] below:

VII. CURRENT DEVELOPEMNETS

After the first patent was filed in 1949[5], the potential of BTT or NSMS is highly realized and all the major gas turbine OEM's and research organization such as NASA, NTRO and others have sponsored programs to mature the technology. Currently, aero-mechanical test of low pressure compressor in MTU, are carried out without the use of strain gauges as reported in [17] and the impetus to use non optical sensors for regular engine health monitoring is actively considered [14] in other organization also.

VIII. FUTURE DEVELOPMENTS IN BTT

Organizations such as PWIG [1], is taking tip timing as a critical measurement technique for the future engine programs and effort are to draw standards for sensors, hardware and analysis techniques. As mentioned in [2], the systems with in-flight capability to acquire and analyze real-time blade vibration data is already underway to study the aeromechanical response of blades. In the past three years 10 patents are published in major journals every year, different working groups setup in all the major engine houses and research organizations are the indices of the future of this promising technology.

IX. LIMITATIONS

Being a non contact measurement without direct strain response directly from the blades, only inferred form FEA results, impacts the reliability considerably in the absence of any proven measurement such as strain gauges. Eventhough the concept of tip timing has matured over the years, the result reported by various researchers are difficult to compare, due to the usage of variety of sensors, hardware and bespoke software developed to suit the individual organization requirements. The algorithm used in the data analysis tools are not standardised enough, hence is difficult to be implemented for any design validation, diagnostics and prognostics purposes. The major drawback of BTT is related to the reliability and endurance of sensors in-service operation in military, civil or industrial applications.

X. DIFFERNET TYPE OF SENSORS IN BTT SYSTEM

The case mounted sensors are the critical elements in the measurement chain and their ability to perform in the hostile engine environment forms the key to the success of BTT. Considerable amount of research [1][23] is focused towards the sensor development which is highlighted by the number of patents registered over the years. Every sensor type has and edge over the other depending on the location fo application in the engine, i.e Fan or Turbine stages and widely reported in literature. The most prominent sensor types such as optical (LASER based), Eddy current or Inductance based, Capacitance, Microwave and Pressure based are being used for measurement in test rigs, engine test, and fight tests [2]. The details about each sensor type their construction, temperature range, temporal and spatial resolution along with their operational merits and demerits are discussed below: [22][6]

XI. SUMMARY AND CONCLUSION

The blade tip timing system exclusively meant to measure rotor blade vibration using case mounted sensors based on the time of arrival technique has come off the age. Efforts by various agencies around the world have led to a higher Technology Readiness Level in the BTT/NSMS systems. More than the conventional strain gauges, which give discrete blade information, BTT can measure the response of all the blades in a stage. Even though, BTT cannot replace strain gauges but the wealth of structural dynamic data of rotor blades enhances the potential of HCF mitigation to a larger extent, thus providing reliable engines with predictable maintenance schedules. The key areas of sensor development and quantification along with a global standardization will lead to the potential use of BTT in in-service engines in military, civil and industrial versions.

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