Engineering Failure Analysis 46 (2014) 26–39

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Vibration based damage detection of rotor blades in a gas turbine engine

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ARTICLE INFO

Article history:
Received 16 April 2014
Received in revised form 26 July 2014
Accepted 31 July 2014
Available online 11 August 2014

Keywords:
Rotor blade vibration
Aero gas turbine
Blade tip timing
Damage
High cycle fatigue

ABSTRACT

This paper describes the problems concerning turbine rotor blade vibration that seriously impact the structural integrity of a developmental aero gas turbine. Experimental determination of vibration characteristics of rotor blades in an engine is very important from fatigue failure considerations. The blades under investigation are fabricated from nickel base super alloy through directionally solidified investment casting process. The blade surfaces are coated with platinum aluminide for oxidation protection. A three dimensional finite element modal analysis on a bladed disk was performed to know the likely blade resonances for a particular design in the speed range of operation. Experiments were conducted to assess vibration characteristics of bladed disk rotor during engine tests. Rotor blade vibrations were measured using non-intrusive stress measurement system, an indirect method of blade vibration measurement utilizing blade tip timing technique. Abnormalities observed in the vibration characteristics of the blade tip timing data measured during engine tests were used to detect the blade damage. Upon disassembly of the engine and subsequent fluorescent penetrant inspection, it was observed that three blades of the rotor assembly were identified to have damaged. These are the blades that exhibited vibration abnormalities as a result of large resonant vibration response while engine tests. Further, fractographic analysis performed on the blades revealed the mechanism of blade failures as fatigue related. The root cause of blade failure is established to be high cycle fatigue from the engine run data history although the blades were put into service for just 6 h of engine operation.

1. Introduction

Vibration induced blade fatigue is one of the greatest causes of failures in gas turbines, reported to be up to 42% of total gas turbine failures [1]. Blade vibration in a rotor assembly is unavoidable and inherent in the operation of any gas turbine engine. Therefore the blade design should cater for such excitation forces present, without which vibrations could be a cause of concern leading to blade failure [2]. Blade assemblies such as turbine or compressor stages are subjected to several sources of excitation leading to forced vibration responses that may occur at or near a blade's natural frequencies. The most common types of forced vibration responses are resonant vibration and flutter [3]. The forced vibration response that occurs at blade's natural frequencies is referred as resonant vibration and the one that occurs near blades' natural frequencies is referred as

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http://dx.doi.org/10.1016/j.engfailanal.2014.07.021
1350-6307/

flutter. Both resonant vibration and flutter have the potential to escalate into larger and larger stresses resulting in failures of the blades referred to as high cycle fatigue (HCF) [4]. Since structural motion can affect the fatigue life, performance and integrity of an assembly [5], monitoring rotor assembly response levels is potentially very useful in an operational engine.

Measurement of rotating blade response is traditionally performed using strain gauges mounted on the blade surfaces. This approach has a number of disadvantages such as complex installation procedure, limitation on the number of gauges that can be used and possibility of failure of gauges at high temperatures encountered in turbines [6]. In addition, strain gauges require complicated telemetry or slip ring systems, can interfere with the aerodynamic and mechanical properties of the bladed assembly [7]. To overcome such difficulties posed in the direct measurement of blade vibration using strain gauges, a novel non-intrusive, non-contacting alternate using non-intrusive stress measurement system (NSMS) based on blade tip timing (BTT) technique is employed [8,9]. The advantage of non-intrusive method of blade vibration measurement is that it provides information on all the blades of the rotor and thus the entire rotor stage can be monitored effectively.

NSMS relies on a few proximity probes mounted on the casing above the rotor to record and analyze the signals generated by the motion of rotor blade tips. The probes capture the time of arrival (TOA) of each blade relative to a non vibrating reference, a one-per-revolution (OPR) probe mounted on the rotor shaft. The blade arrival times at the probe locations vary depending on frequency and amplitude of vibrations. The difference between the TOA of a vibrating blade and its computed TOA had it not been vibrating, provides the instantaneous blade amplitude. The present exercise is to ascertain the problem of blade failures and explore ways of preventing them in future on an operating aero gas turbine engine. The present work is divided into following sections:

(i) Three dimensional (3D) finite element (FE) analysis of a low pressure (LP) turbine bladed disk model is performed to estimate blade natural frequencies and mode shapes. The estimated resonances are plotted on a Campbell diagram.
(ii) Experimental resonance characterization of LP turbine bladed disk rotor is conducted by capturing blade arrival times of the rotor using NSMS. The rotor resonances thus obtained are represented on a Campbell diagram.
(iii) In-situ detection of the blade damage is illustrated using the abnormalities observed in blade vibration characteristics through an observable change in blade resonant amplitude and mechanical blade lean in three of the blades during engine operation.
(iv) Fluorescent penetrant inspection (FPI) and fractographic analysis corroborate the damaged blades ascertained from engine experimentation as fatigue related failures.

2. Background

LP turbine rotor blades are made of nickel base super alloy of CM – 247 LC alloy. The blades are fabricated by directionally solidified (DS) investment casting process and coated with platinum aluminide diffusion coating. Post failure analysis conducted during earlier occasions indicated that the cause of blade failures were due to abnormally high stresses in the so called rogue blades in the rotor assembly. The mechanism of blade failures were observed as fatigue related. This had led to an extensive study on LP turbine rotor vibration characteristics by measuring the deflection at the blade tips through a non-intrusive technique of blade vibration measurement using NSMS. Full-scale engine tests of an aero gas turbine were performed with this novel instrumentation in place. This paper quantifies the blade vibration parameters through measurement using NSMS and provides strategy for on-line damage detection to avoid catastrophic blade failures in future.

3. Modeling and analysis

Dynamic analysis [10] of a LP turbine rotor blade and disk FE model is performed using ANSYS mechanical 12.0. Crack element is not considered in this model since safe-life design approach is followed in the present work. True boundary conditions are applied. The loads considered are centrifugal, thermal and aerodynamic. The blade natural frequencies and mode shapes are predicted. Based on the predictions, a Campbell diagram is plotted that indicates the likely resonances for a particular design of the rotor blade in the speed range of operation. However some researchers have performed dynamic analysis of rotating blades with cracked hexahedral finite element method [11], which is applicable for damage-tolerant design approach.

3.1. Material properties

Material properties of the DS blade at room temperature are density, 8530.0 kg/m^3 and Young's modulus, 120.0 GPa. Blade natural frequency is a function of the Young's Modulus of the material and its density. Mathematically,

$$f \propto \sqrt{\frac{\boldsymbol{E}}{\boldsymbol{\rho}}}, \quad \text{where}$$