TURBINE BLADE CRACK DETECTION USING VIBRATION TESTING METHODS

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requirements for the award of the degree of
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To Papa, Mama and Tan Lin
for their support and love

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ABSTRACT

Turbine blades are the most common cause of failures in gas turbines. Failure modes are typically cracking from foreign object damage (FOD), high cycle stress (HCF), blade rubbing, degradation from erosion and corrosion. Fault detection of blades is important function in reducing blade related failures. This study involved the use of vibration analysis and dynamic testing of blades for failure detection. Current field inspections of blades are based on visual inspections only, and the intent here was to use impact testing of the blades during these inspections to determine cracked blade (from the vibration response). Vibration impact tests were undertaken using decommissioned turbine blades with and without cracks in the laboratory. Four common crack patterns were deliberately induced to the turbine blades to investigate changes in the blades normal mode response. Finite element analysis (FEA) of the blades was also undertaken. FEA results were correlated to experimental results and these results showed that each crack pattern was unique and significant changes were found in higher modes. Dynamic vibration analysis was also undertaken in a laboratory testrig fitted with rotating model straight blades. Vibration measurements were undertaken on a baseline test case and other test conditions where the blades had induced cracks. Steady state and transient vibration responses were obtained from the controlled tests. Vibration measurements were on the machine casing and on a blade (with an accelerometer surfaced mounted onto a rotating blade). Order tracking analysis and continuous wavelet analysis were performed to the measured data. Both techniques showed ability in detecting changes in vibration response on the blades and casing for blades with cracks. Results showed that significant changes were detected during transient analysis as compared to the steady state. Changes were noted in the vibration response corresponding to the machine running speed and blade passing frequencies. Changes in wavelet maps were however qualitative in nature, which suggested that more work need to be undertaken for cracks severity assessment using wavelet maps.

ABSTRAK

Bilah turbin adalah salah satu punca utama yang menyebabkan kegagalan dalam turbin-turbin gas. Kegagalan biasanya terjadi disebabkan oleh kerosakan objek asing (FOD), tekanan kitaran tinggi (HCF), geseran bilah dan degradasi daripada hakisan dan kakisan. Kajian ini melibatkan penggunaan analisis getaran dan ujian dinamik bilah turbin untuk mengesan kegagalan bilah. Tujuan kajian ini adalah dengan menggunakan ujian impak bilah bagi menentukan kegagalan bilah (daripada tindakbalas getaran). Ujian impak getaran ini telah dijalankan dengan menggunakan bilah turbin yang mempunyai dan tidak mempunyai retakan. Empat jenis corak retak telah dikenakan pada bilah turbin bagi mengkaji perubahan pada bilah turbin itu ketika dalam mod yang biasa. Analisis unsur terhingga bilah turbin juga dijalankan. Keputusan analisis unsur terhingga telah dikorelasikan dengan hasil keputusan kajian. Keputusan ini menunjukkan bahawa perubahan setiap corak retakan adalah unik dan penemuan ketara telah ditemui dalam mod yang lebih tinggi. Analisis getaran dinamik telah dijalankan di alatan ujian yang dipasang dengan bilah turbin lurus yang berputar. Getaran mantap dan getaran fana diperolehi dari ujian yang dikawal itu. Pengukuran getaran dilakukan pada penutup mesin dan pada salah satu bilah (dengan satu meter pecutan yang dilekatkan pada bilah yang berputar). Analisis pengesanan arah (order tracking) dan analisis gelombang kecil (wavelet analysis) selanjar dilakukan pada data yang diperolehi. Kedua-dua teknik ini menunjukkan keupayaan dalam mengesan perubahan tindakbalas getaran. Keputusan menunjukkan perubahan yang ketara telah dikesan semasa analisis fana berbanding pada keadaan mantap. Perubahan telah dikenalpasti di dalam tindakbalas getaran berdasarkan kepada halaju mesin dan frekuensi halaju bilah. Perubahan dalam peta gelombang kecil bagaimanapun adalah secara semulajadi dan dicadangkan bahawa kajian yang lebih mendalam perlu dilakukan bagi mengesan retakan yang teruk dengan menggunakan peta gelombang kecil.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BPS	-	Blade Passing Frequency
CWT	-	Continuous Wavelet Transform
Hz	-	Hertz
FFT	-	Fast Fourier Transform
FOD	-	Foreign Object Damage
FRF	-	Frequency Response Function
PDS	-	Power Density Spectrum
RPM	-	Revolution per minute
STFT	-	Short Time Fourier Transform

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Gas turbines are common but critical machines used in power generation, petrochemical and heavy industries. Unscheduled down time often result in economic losses exceeding RM1milliom per day [1]. With such economic losses quick diagnosis and trouble shooting is required. [2] Manufactures such as General Electric [3], recommends 3 types of maintenance inspections namely standby, running and disassembly inspections to prevent unscheduled down time. Turbine blades being key components of the gas turbine which suffers high mechanical loading due to drastic changes in both temperature and pressure. [4] These often result in mechanical failures such as cracking, blade rubbing, degradation etc which are often detected only during the Hot Gas Path Inspection under the disassembly inspection [3]. Figure 1.1 provided an overview of the work scope during the inspection. Minor repair could be carried at the same time. Tim J Carter (2004) reported that turbine blade suffered most damage from crack which were either caused by foreign object damage (FOD) or torsional forces. This is illustrated in the figure 1.2. This figure shows possible turbine blade failures and the percentage distribution. Cracks on surface, like which occurs on aerofoil & lashing area are not as harmful as compared those in the blade root and disk root area; as long the failure

does not penetrate through the blade body. These are also relatively easier to be detected during the visual inspection by applying the Fluorescent Penetrate Inspection (FPI) or non- Destructive Inspection (NDI) [3]. Cracks adjacent the blade clamp area are potentially very serious as it is not so visual and are difficult to detect unless during the Major Inspection [3] where all turbine blades would be removed from the rotor. The percentage of blade root cracking is also significant. This is illustrated in figure 1.3. It had been reported that cracks in the air-flow lead and trailing edge also recorded high percentage. Normally the stress rupture crack will appear in these areas. The latter experiments would be based on these crack patterns.

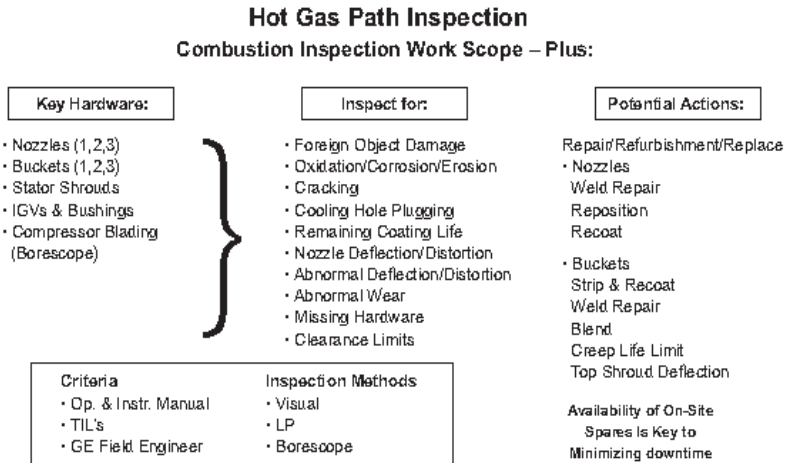

Figure 1.1 Key element for Hot Gas Path Inspection

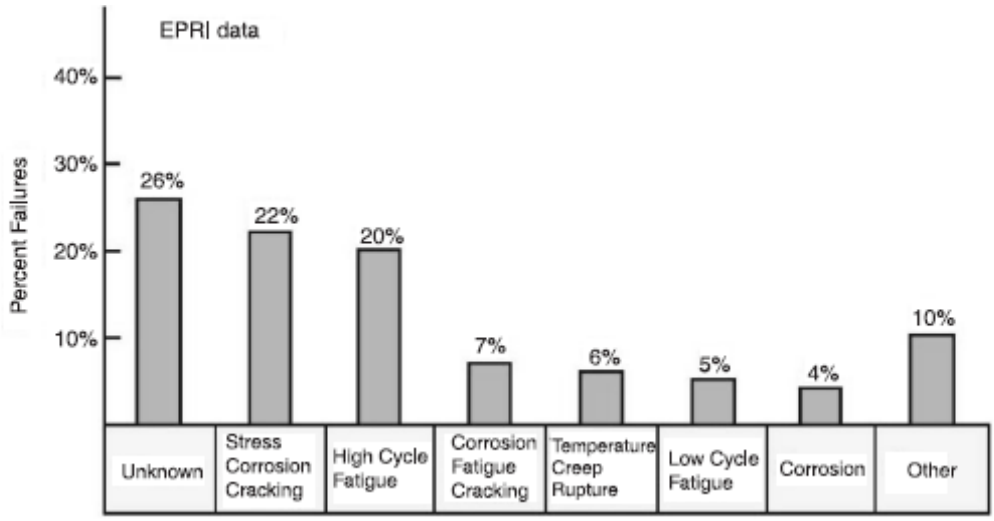

Figure 1.2 Mechanism reported to have cause the turbine blade failures (Dewey & Rieger 1982; Dewey & McClokes 1983; Dewey & Rieger 1983; Artens *et al* 1984)

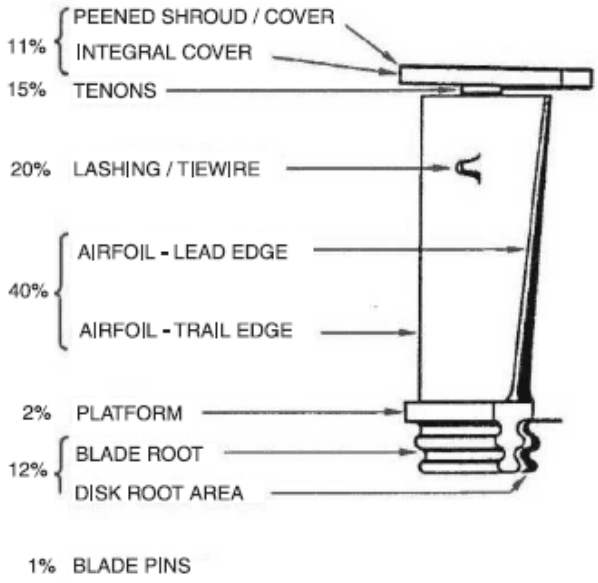

Figure1.3 Location of LP turbine blade failures (Dewey & Rieger 1982; Dewey & McClokes 1983; Dewey & Rieger 1983; Artens *et al* 1984)

1.2 Subject Background

A gas turbine is a complicated machine. A turbine blade has to withstand the vibratory stresses, flexural stresses, centrifugal force etc. Basically the vibratory stresses are induced by aerodynamic forces. These forces are introduced by the combusted gas that flow through the stages of blades. Centrifugal forces are the side effects of the gas turbine rotational movement. Increase of the rotational speed would double up the forces value; therefore proper blade design is very important. The flexural stresses are generated by the motion of the blade that causes an unsteady pressure field around the blade sustaining the vibration. This excitation is initialed by small mechanical or aerodynamic disturbances above the critical flow speed.

Turbine blade life cycle is influenced by factors which under two main categories: design and operation conditions; Operation condition are more critical category. Blades have to maintain its integrity under severe operation conditions which result in high mechanical stress and high thermal stresses [5].

Turbine blades operate at high temperatures, typically up to 1000^0C. At the same time blades are exposed to contamination issue mainly from burning fuel and intake air. Foreign object damage (FOD) is a common occurrence where blades are damages with material removed from impurities and foreign objects impinging on the blades.

Thermal stresses occur in the blade when the blade is experiencing the large scale thermal gradient. This often happen during the transient states like run up or coast down. This stress normally concentrated to the tip or edges or of the blade which results in crack on the blade.

Blade vibrations are often examined under two different perspectives: self excited vibration and forced vibration. Self excited vibration is often known as flutter. It is an aero-elastic self-induced vibration with a sustained amplitude, normally seen at high speed rotation with no external forces involved. Force vibration is induced by flow disturbances when working fluids pass through the stages. This would results in an impulsive force to the blade body.

Blade vibration could only be measured from the casing and under such situation would not off any direct measurement of the blade induced vibration. Even though the blade vibration could not be measured directly, blade related diagnosis still could be done from examination of response related to blade pass frequencies (BPF).

The BPF is the pulsation force which occurs in bladed assembly. This force is generated from the pressure fluctuation as a rotating vane or blade passes stationary components like stator or housing. The stationary component produces a non-uniform flow disturbance in the gas field. In vibration analysis, the number of blades multiplied with the RPM of the rotor supporting the impeller physically defines the blade passing frequency (BPF). The amplitude corresponding to the BPF is small. An increase in the vibration amplitude of the BFP is usually due to:

(i) A housing or rotor eccentricity
(ii) Vane or blade wear (abrasive materials)
(iii) Bent, loose or misaligned housing diffuser vane
(iv) A resonance Excitation

1.3 Problem Statement

The manufacture's Major Inspection undertaken for gas turbine is expensive and requires a long downtime. It is usually scheduled according to the manufacturer's recommendations or based on findings of previous inspection results. This is normally undertaken 2-3 years after the turbine's initial operation. With thermal stresses from periodic on-off, turbine blade cracks had known to occur rapidly with serious consequences prior to the Major Inspection. [6]

It is then very important to indicate the present of cracked blade from the non-invasive measurements or procedures such as vibration. The current operational vibration monitoring which mainly focus on overall vibration value, showed insufficient sensitivity in detecting the cracked blade. Vibration FFT plots obtained under steady state condition are also not sensitive enough for the detection of cracked blade. Sophisticated analysis method such as order tracking, power density spectrum and wavelet analysis could be considered to be used in maintenance inspection especially it shown to be able to detect crack blade.

The visual inspection undertaken during maintenance relies on visual means and human interpretation. Minute cracks or blade root crack could be missed out easily during the visual inspection. A scientific based method such as the impact test could be used as a more reliable tool to assist the visual inspection during maintenance.

An understanding of dynamic behavior of a cracked blade needs to be obtained prior to application in the maintenance inspection.

1.4 Objectives of the study

The objective of this study was to assess the practicability of vibration based test method in detecting cracks in turbine blade. This can be explained as follow,

1. To verify the effectiveness of vibration impact test to capture the turbine blade crack in a minor inspection. This required the study cracked blade response from the impact tests.
2. To model a blade with or without cracks using FEA method. Computational results would be correlated against the measurement results.
3. To study which vibration analysis methods (order tracking, FFT and wavelet) for a rotating blade assembly for the detection of a cracked blade from the measured vibration response.

1.5 Scopes of the study

The scope of this research were limited to the followings,

1. The identification of a common crack patterns that occur in real blades.
2. An experimental study for vibration response of stationary blades from impact test for blades with the common crack patterns..
3. The comprehension of cracked blade effects from computational model and modal analysis.
4. An experimental study of vibration measurement analysis for a rotating bladed assembly with induced cracks in a test rig.