

BLADE FAULTS DIAGNOSIS IN MULTI STAGE ROTOR SYSTEM BY MEANS OF WAVELET ANALYSIS

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Specially dedicated to my beloved family
Ahmed

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ABSTRACT

Blade fault is one of the most causes of gas turbine failures. Vibration spectral analysis and blade pass frequency (BPF) monitoring are the most widely used methods for blade fault diagnosis. These methods however have limitations in the detection of incipient faults due to weak and/or transient signals, as well as inability to diagnose the blade faults types. This study investigates the applications of wavelet analysis in blade fault diagnosis of a multi stage rotor system, as an extension of previous works which involved a single stage only. Results showed that conventional wavelet analysis has limitations in segregating the BPFs and locating the faults. An improvement in Morlet wavelet was made to achieve high resolution in both time and frequency domains. Two new wavelets for high time-frequency resolutions were formulated and added to the standard MATLAB Wavelet Toolbox. The optimal parameters for the high frequency resolution wavelet were found at the centre of frequency, $F_c = 4$ and bandwidth, $\beta = 0.5$. For high time resolution wavelet, the optimal parameters were $F_c = 4$ and $\beta = 10$. A novel algorithm was formulated by combining the two newly developed wavelets. A variety of blade faults including blade creep rubbing, blade tip rubbing, stage rubbing, blade loss of part and blade twisting were tested and their vibration responses measured in a laboratory test facility. The proposed method showed potential in segregating closely spaced BPFs components and identifying the faulty stage and fault location. The method demonstrated the ability in differentiating various blade faults based on a unique pattern (“fingerprint”) of each fault produced by the newly added wavelet. The formulated algorithm was demonstrated to be suitable in monitoring rotor systems with multiple blade stages.

ABSTRAK

Kerosakan bilah adalah salah satu punca yang paling kerap menyebabkan kerosakan turbin gas. Analisis spektrum getaran dan pemantauan kekerapan laluan bilah (BPF) adalah satu kaedah yang sering digunakan untuk mendiagnos kerosakan bilah. Kaedah ini bagaimanapun mempunyai batasan dalam pengesanan kerosakan kerana isyarat yang lemah dan/atau fana serta ketidakupayaan untuk mendiagnos jenis kerosakan bilah. Kajian ini mengkaji penggunaan analisis *wavelet* dalam diagnosis bilah yang rosak dalam sistem rotor berbilang peringkat sebagai. Lanjutan terhadap kajian sebelum ini yang hanya melibatkan peringkat tunggal sahaja. Keputusan menunjukkan bahawa analisis *wavelet* biasa mempunyai kelemahan dalam mengasingkan BPF dan mengesan kerosakan. Penambahbaikan terhadap *wavelet* Morlet telah diusahakan untuk mencapai resolusi yang tinggi dalam domain masa dan frekuensi. Dua *wavelet* baru untuk resolusi frekuensi dan masa yang tinggi telah digubal, ditambah dan digunakan bersama kepada perisian MATLAB/Wavelet Toolbox. Parameter optimum untuk *wavelet* frekuensi tinggi resolusi adalah pusat frekuensi, $F_c = 4$ dan $\beta = 0.5$. Parameter optimum untuk *wavelet* resolusi tinggi masa adalah jalur lebar, $F_c = 4$ dan $\beta = 10$. Satu algoritma novel telah dibangunkan dengan menggabungkan dua *wavelet* baru. Pelbagai kerosakan bilah, termasuk geselan bilah disebabkan oleh rayapan geselan hujung bilah, geselan peringkat, kehilangan bahagian bilah dan bilah terpiuh diuji dan respon getaran diukur menggunakan kemudahan ujian dalam makmal. Kaedah yang dicadangkan menunjukkan keupayaan dalam mengasingkan komponen ruang rapat BPF dan mengenal pasti peringkat dan kedudukan kerosakan. Kaedah tersebut mempamirkan keupayaan dalam membezakan pelbagai kesalahan bilah berdasarkan corak yang unik ("cap jari") setiap kerosakan yang dihasilkan oleh *wavelet* baru. Algoritma yang dibentuk mempamirkan kesesuaian dalam memantau sistem rotor dengan bilah berbilang peringkat.

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LIST OF ABBREVIATION

AE	Acoustic Emission
BPF	Blade Passing Frequency
B.P.R	Blade point rubbing
B.T	Blade twisting
C	Celsius
C.B.R	Creep blade rubbing
CFD	Computational Fluid Dynamics
CWT	Continuous Wavelet Transform
DSP	Digital signal processor
DWT	Discrete Wavelet Transform
EDMS	Engine distress monitoring system
Hz	Hertz
FFT	Fast Fourier Transform
LOP	Loss of Part
OS	Operating Speed
rpm	Revolution per Minutes
STA	Synchronise Time Averaging
STFT	Short Time Fourier Transform

LIST OF SYMBOLS

a	Wavelet dilation parameter
b	The location parameter of the wavelet
cm	Centimetre
$DELTA$	The sampling rate (1/sampling frequency)
d	Diameter
Fa	Pseudo-frequency of Wavelet
Fc	The centre frequency of a wavelet in Hz and
Fs	Sampling frequency
g	Gram
mm	Millimetre
N	Number of blades
n	1, 2, 3, etc.
$W(a, b)$	The wavelet transform
$wname$	The wavelet name
β	Bandwidth of Morlet wavelet
ψ	Wavelet Function
$\psi_{a,b}$	The mother wavelet
$\Psi(t)$	Wavelet function
$\psi^*(t)$	Complex conjugate
σ_t	The energy spectra temporal deviations
σ_ω	The energy spectrum standard deviation
Δ	The sampling period

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CHAPTER 1

INTRODUCTION

1.1 Overview

Rotating machinery such as turbines and compressors are critical equipment in power generation and petrochemical plants. Machinery typically consists of a number of parts including inlet, combustion chambers, shafts, blades, vanes, combustors among others. These components are designed to dictate the gas paths of the working fluid to generate thrust and/or power. The bladed assemblies typically are multiple stage. In these machines, there could be more than multiple blades located in both the turbine and compressor sections for the transfer energy between the rotor and the working fluid. Satisfactory operation of these machines is largely dependent on the condition of these blades. A high level of reliability is required where failure detection and diagnosis are of great importance to achieve the required reliability.

Components of gas turbine in the hot regions and parts such as blades, vanes and combustors are exposed to high temperatures, with inherent high stress and quite often in a potentially high vibration environment during operations. The gas turbine blades which under normal operation are exposed to exceed 1400°C at inlet and a 40 bar pressure, for which energy extraction from high temperature and high pressure gas are obtained. Exposure to very high temperatures and pressure inherently lead to potential metallurgical related damages, often limiting their designed operational life. The damages to blades include creep, micro-structural instability and embrittlement,

oxidation, thermal fatigue, hot corrosion, vibration, foreign object damages; which consequently increases the probability of premature blade failure. The failure of a single blade can potentially compromise the total integrity of the machine [1].

There are also a number of process and factors which influences the blade health and its overall life in addition to the effects of damages. The blades are subjected to centrifugal forces due to high rotational speed, bending stresses by the moving gas stream in the presence of a highly oxidizing atmosphere at high temperature and thermal stresses due to the temperature gradient. Blades are typically made from nickel base super-alloys that have a superior high temperature strength together with a high degree of corrosion and oxidation resistance [2]. Blade health monitoring, failure diagnosis and maintenance are hence very important to ensure operation with high efficiency, safety and reliability for cost effective of operation and maintenance.

Blade failures represent the highest percentage of failure in gas turbines. As cited by Meher-Homji [3], Allianz Insurance Company one of the biggest insurance companies in the world reported that blade failure accounted for 42% of the total failures in gas turbines. Statistics of steam turbine faults in China power generation over several decades also showed that blade faults are the most frequent and highest percentage of failure, especially during the 1980s. In the 1990s and the 21st century, blade fault causes however decreased compared to 1980s [4]. This was probably due to the innovative development in blade design, blade manufacturing technology and improvements in blade fault diagnosis accuracy as compared to the previous decade.

Farrahi et al. [5] and other researchers [6, 7] reported that, blade failures in gas turbines and compressors, originate mainly from some form of initial damage or defect of the blades caused by Foreign Object Damage (FOD), ingested debris or manufacturing defects. These minor defects or damages propagate over time eventually leading to total blade failure. Blade faults and blade failures in turbomachinery are generally classified into the following categories: blade rubbing, cracking and foreign object damage (FOD) or loss of part, blade deformation

(twisting, creeping, corrosion and erosion), blade fouling and rotating stall, blade fatigue failure, and blade root attachment problems (root crack and loose blade). Incipient failure in the blade can potentially lead to catastrophic failures. Figure 1 below shows some of the blade failures.



Deformation of rotor blades , Source: [8]



Failure of 1st row of blades, Source [9]



Catastrophic blades damage, source [10]



Broken blades at different stages [11]

Figure 1.1 Typical Blade Failure

Blade condition monitoring involves the measurement and the assessment of various parameters related to the blade (such as vibration, temperature, pressure, oil debris, performance acoustic measurements, etc.). Monitoring of these parameters could potentially determine whether the blade is in good or bad health condition.

1.2 Problem Statement

Turbine blade faults diagnosis had been a subject of research in recent decades. There had been a number of methods developed for this purpose which includes acoustic emission measurement, blade tip measurement, pressure, strain gauge, debris monitoring, optical measurements, temperature measurements, performance monitoring, among others. Although most of these methods were shown to be effective in varying degree for blade faults diagnosis, a major difficulty relates to its use under practical field conditions. A further issue related to faults detected only after the faults are in advanced stage of catastrophic failure, or when parts are already damaged.

For application under practical field condition, vibration based methods inevitably represents the most readily and widely used methods for blade fault diagnosis. This is due to the fact that vibration signals are directly related to the response of the machine structural dynamics due to changes in working conditions within the machine. Vibration signals are conventionally analysed with Fourier analysis to obtain the vibration spectrum, with blade passing frequency (BPF) being the most commonly used primary parameter for detection of blade faults. Relative changes in blade passing frequency and its harmonic amplitude could provide useful information upon which blade faults could be detected [12-15].

Blade faults are however difficult to be detected during normal machine operations, and vibration analysis can only detect blade faults if severe damage occurs at the blade [16-19], where minor blade faults not so readily detected. Common vibration diagnosis techniques are based on frequency domain analysis with changes to be detected in the vibration spectra (i.e. escalating BPF amplitude). The vibration amplitude is deemed an indicator of severe blade damage occurrence and used for assessment of any imminent failure. Field experiences however had been shown that blade faults do not result in significant increase in the overall vibration amplitude as the overall vibration amplitude are dictated by the synchronous unbalance response of the machine.

Recently, Lim [20] in recent years had shown that the sensitivity and reliability of vibration analysis for blade faults diagnosis can be improved with wavelet analysis based on tests in a test rig with single blade row. Wavelet analysis and its time-frequency display could provide a clearer picture of blade faults signature, hence providing better visualization of the blade conditions in comparison to vibration spectra. Wavelet analysis was shown to be more sensitive in blade fault diagnosis with the capability of distinguishing various blade fault conditions such as creep rub, eccentricity rub, which are not so readily detected using vibration spectra analysis.

Blade fault diagnosis is still a challenging problem especially in multi stage machines. Research on multiple stages of blade faults using wavelet analysis is lacking. In real machines blades are often multi-stage with different blade pass frequencies which pose challenges in the use of wavelet analysis for fault detection.

1.3 Problem Formulation

The conventional blade fault diagnosis methods (Fast Fourier Transform (FFT) analysis) which are based on frequency domain analysis assumed that the BPF signal is stationary during the analysis period. This assumption that however is not true which render such methods not effective for blade fault diagnosis. This is because the operating conditions in the real machine are often non-stationary and there are a number of transient periods. This may sometimes lead to incorrect analysis consequently resulting in missed detections. Conventional FFT methods do not provide any time information thereby making it unsuitable for fault detection in the time domain. Wavelet analysis has been recently used as the alternative method for blade fault diagnosis to overcome the limitations of FFT technique.

For multi-stages rotor systems, the vibration signal is inheriting more complicated as it contains a number of closely located frequency components in the

vibration spectrum. It is often difficult to analyse a signal with a composite frequency component and to differentiate the closely located frequency modes because of the interference term. It is important in time-frequency analysis to achieve the best time-frequency energy localization for the given signal. Localization is often employed to locate the arrival time and estimate the dispersed frequency of the signal.

This study attempts to formulate a method for the detection and diagnosis of blade faults in a multi-stage rotor system. Previous works undertaken by Lim [20] involved a single blade row only. Even with novel methods for blade vibration monitoring using wavelet analysis, artificial intelligence and neural network, BPF is still the fundamental parameter used in these methods. It is believed that blade passing frequency signals contain more useful information; and if correctly monitored could indicate the current condition of the rotating blades. Wavelet analysis provides additional features (such as signals analysis with multiple scales, and non-stationary processes, breakdown points, discontinuities, and self-similarities) to enhance the signal processing. This suggested potential merits to investigate the suitability and applicability for monitoring blade passing frequency signals in a multi-stage rotor system with an aim of applying it to blade faults diagnosis.

The study was intended to examine the visibility of using wavelet analysis for multi-stages blade fault diagnosis, including matters related to BPF signal extraction, separating the close BPF components, blade faults (detection, discrimination and localization), results interpretation and possibilities of establishing fault signatures.

1.4 Research Questions

This work attempted to address the following research questions:

1. Does the captured casing vibration signal contain useful information about the BPF components of different stages of a motor rotor system?
2. Is the wavelet analysis technique capable of analysing, separating the closely located BPFs components with an intent to identify the faulty stage and the location of the faulty blade?
3. If the wavelet analysis technique is incapable of segregating the BPFs components of the multi stage rotor system, how can it then be adopted for segregating the BPFs components in multi stage rotor system blade faults diagnosis?
4. Does wavelet analysis techniques have the capability of detecting and diagnosing single fault in multiple stages or multiple faults in multiple stages?
5. How can the above issues can be addressed, and hence used to establish the blade faults signatures?

1.5 Objectives of Study

The objectives of the research were to investigate the use of wavelet analysis for detection and diagnosis of blade faults in multi stage blade assemblies. This included the formulation of wavelet function for blade faults detection and identifying type of fault. The work scope included but was not limited to the following:

- a) Examination of feasibility of wavelet analysis in multi stage rotor system for blade faults diagnosis using signal simulation and experimental study.
- b) Formulation of a suitable diagnostic method for blade faults in a multi-stage rotor system and validation.

- c) Undertaking of laboratory testing of induced faults in a multi array using an experimental test rig based on formulated wavelet analysis technique on the extracted BPF signals.
- d) Establishing fault signatures from the controlled faults with identification of fault characteristics.

1.6 Significance of the study

An effective and sensitive diagnostic technique for various types of blade faults is most critical in service operational machines especially for reliability assurance. To avoid costly catastrophic failures, early detection of incipient and including minor and transient blade faults is necessary because these early faults can lead to total blade failures, which often result in a catastrophic failure of the entire turbine. Previous work by Lim [20] was based on a single stage blade rows only with a single fault in single stage or multiple faults in a single stage. That setup meant that other possible cause of failures such as a single fault in multiple stages and multiple faults in multiple stages were not considered. This study was intended to extend the applications to real operation in the field for machines with multi-stage blade assembly which are typically in gas turbines and compressors.

1.7 Thesis Structure

Chapter 1 introduces the background of the study, objectives to be met and its significance. Chapter 2 presents critical reviews on the concepts of blade fault diagnosis, and analyses the different strategies used in condition monitoring of the blade in turbo machinery. Chapter 3 presents the methodology of this research work, a road map on how the research activities of this study. In Chapter 4, a discussion of the experimental test rig design is provided with validation and details of the

experimental setup discussed. The feasibility of FFT and wavelet analysis in analysing a multi-stage rotor system signal using simulated signals and experimental data is discussed in Chapter 5. Vibration characteristics of a multi-stages rotor system were examined in context of limitations and difficulties in conventional wavelets in analysing a multi-stage rotor signal. Chapter 6 presents the wavelet reassignment technique, highlighting the function of the newly proposed wavelet technique to the multi-stage blade fault diagnosis. In Chapter 7, the experimental studies undertaken are presented. Results and discussion of the experimental study are presented in Chapter 8. Conclusion and the recommendations for future research work are summarized in Chapter 9.

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