*Review Article*

# Condition Monitoring of Blade in Turbomachinery: A Review

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Blade faults and blade failures are ranked among the most frequent causes of failures in turbomachinery. This paper provides a review on the condition monitoring techniques and the most suitable signal analysis methods to detect and diagnose the health condition of blades in turbomachinery. In this paper, blade faults are categorised into five types in accordance with their nature and characteristics, namely, blade rubbing, blade fatigue failure, blade deformations (twisting, creeping, corrosion, and erosion), blade fouling, and loose blade. Reviews on characteristics and the specific diagnostic methods to detect each type of blade faults are also presented. This paper also aims to provide a reference in selecting the most suitable approaches to monitor the health condition of blades in turbomachinery.

## 1. Introduction

Blades are extensively used in power generation turbomachinery such as the compressors and gas turbines. In these machines, there could be more than a thousand blades located in both the turbine and compressor sections to transfer energy between the rotor and fluid. Thus, the operation of these machines is largely dependent on the condition of these blades. Blades often operate in hostile and high stress environment that can potentially lead to blade failures. The failure of a single blade can potentially compromise the total integrity of the machine. In such instances, even a blade failure rate of 1 in 1000 is not acceptable. According to Farrahi et al. [1] and Poursaeidi et al. [2], blade failures in gas turbines and compressors mostly originate 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 damage can propagate over time and eventually lead to total blade failures. Common types of blade faults and blade failures in turbomachinery include blade rubbing, low and high cycle fatigue failures, creep, fouled blade, loose blade, and blade induced FOD. A review on the most common failure mechanisms in gas turbine blades was provided by Carter [3].

This paper provides a review on the strategy for monitoring the condition of blades as well as the specific techniques applicable to monitoring different types of blade faults commonly found in turbomachinery.

## 2. Strategies for Condition Monitoring of Blade

Two different types of strategies can be employed to monitor the condition of a blade: monitoring machine's operating parameters (e.g., vibration, pressure, temperature) and performing signal analysis (e.g., Fourier's analysis, wavelet analysis, artificial intelligence). In most instances, both strategies are deployed concurrently to obtain the most important information from the signal at hand. In this paper, the literature review on each of these two strategies is presented.

### 2.1. Monitoring of Machine's Operating Parameters

*2.1.1. Vibration Measurements.* Vibration analysis has been the most widely used blade condition monitoring method

for decades. Time domain waveform signals are typically transformed into the frequency domain using Fourier's transformations. After that, interpretation of the vibration spectrum is performed to extract useful information about the health of the machine. Detailed monitoring of a blade using vibration analysis is commonly achieved by monitoring the relative changes of its blade pass frequency (BPF) and its harmonics as presented by Mitchell [4]. The use of vibration analysis for blade faults diagnosis has also been studied by Simmons [5, 6], Parge et al. [7], and Parge et al. [8]. They have observed that the relative changes in the BPF and its harmonics amplitude can provide useful information about the occurrence of blade rubbing. Al-Badour et al. [9] studied the vibration signals caused by stator-to-blade rubbing during the machine runup and coast-down and they found that this method is effective in detecting blade rubbing. The authors Abdelrhman et al. [10] also investigated the effectiveness of vibration analysis for blade rubbing in multistage rotor system at different rotor stages and different rubbing severities. Satyam et al. [11] used Cepstrum analysis to analyze the vibration signal in order to detect blade faults. It was shown that the conventional frequency analysis in machinery vibration is incapable of accurately determining the defects in blades. On the other hand, Cepstrum analysis can accurately identify the harmonics and sideband families of BPF. It is therefore a better technique for blade faults detection especially in ship and submarine applications. In addition, Randall and Sawalhi [12] also employed the same technique to remove unwanted frequency components from the BPF components of interest. This allows for a better identification of blade fault based on the BPF monitoring approach. Mathioudakis et al. [13] conducted an experimental study to correlate between the compressor casing vibration and the pressure field around the compressor blades. They found that the casing vibration can be correlated with unsteady pressure field around blades and thus provide a clearer picture of the blade in the interior of the casing as compared to conventional vibration signals. Barragan [14] reported that through a detailed comparison of vibration spectrum against a vibration spectrum library of severe faults such as FOD, blade loss part, blade rub, and loose joints, blade fault could be detected. Chang and Chen [15] studied the detection of cracked blades by analyzing vibration signals with a spatial wavelet analysis method. They found that the position of the cracked blade can be identified based on the proposed method. Zielinski and Ziller [16] presented a noncontact blade vibration measurement method on axial flow turbine compressor blades. This method offered a better means of detecting cracks in rotor blades. Nevertheless, it is highlighted by Baines [17] that vibration analysis could only detect the blade faults if severe damage occurs at the blade. A minor deformation of a few blades, such as rubbing, will not be detected. Hee and Leong [18] used vibration signal to generate operational deflection shape (ODS) of rotor casing to detect blade rub. A comprehensive review on the use of vibration as a diagnostic tool for blade fault has been done by the authors and can be found in [19].

*2.1.2. Strain Gauge Measurements.* Strain gauges are typically used to measure the amount of deformation on the surface of a turbine blade. Scalzo et al. [20] employed the strain gauge method to monitor the stress profile of blades of an industrial gas turbine. It is reported that this method enables the monitoring of blade fatigue failures by studying the characteristic of flow-induced resonant vibration. It is well understood that a crack presence in a turbine blade will alter its natural frequency and a cracked blade may thus experience resonance conditions even at its normal operating condition. Mercadal et al. [21] proposed the use of noncontacting stress monitoring system (NSMS) to monitor blade's resonance whereby a damaged blade is found to have shifted in its resonant frequencies. A method of using strain gauge to monitor low cycle fatigue faults in turbine blade was also proposed by Kumar et al. [22]. Barschdorff and Korthauer [23] commented that the deployment of this method in operational gas turbine may face some challenges as the strain gauge device may fail due to the extremely high temperature in the gas turbine.

*2.1.3. Pressure Measurements.* The use of pressure field distortion around rotating blades was proposed by Mathioudakis et al. [13] to diagnose blade deformation faults. It was shown that the pressure transducer signals mounted in the inner casing of the industrial gas turbine provide better information about the condition of fouled and twisted blades than the vibration analysis. This method has also been studied by Barschdorf and Korthauer [23] and Valero and Esquiza [24]. However, it is reckoned that this method is difficult to employ for operational gas turbines due to the difficulty of mounting pressure sensors at the surface of turbine blades.

*2.1.4. Acoustic and Acoustic Emission Measurements.* Acoustic emission techniques have proven to be an effective tool for early fault detection in rotating machinery [25]. Leon and Trainor [26] presented an online blade fault diagnostic method based on acoustic signals. This method utilized internal mounted acoustic sensors to identify the occurrence and location of propagating blade cracks, blade row damage, blade flutter, and aerodynamic events such as condensation shock. Willsch et al. [27] introduced a new technique for online monitoring of blade cracks and spalling. This technique involves the use of acoustical waveguides, optical waveguides, and millimeter waves. Nonlinear acoustics measurements techniques were then employed to evaluate fatigue in turbine blades. Nonlinear acoustics measurements techniques were also applied by Hinton et al. [28] to monitor blades fatigue. Randall and Rocketdyne [29] and Graham et al. [30] introduced blade faults diagnostic method based on acoustic emission monitoring to detect faults such as blade-to-stator rubbing, loose turbine disks, and blade cracking. The use of acoustic emission (AE) in monitoring gas turbine operating parameters is also investigated by Douglas et al. [31]. An experimental study done by Banov et al. [32] and Urbach et al. [33] showed that when fatigue crack has become sufficiently long, AE techniques can be used to effectively detect cracks of blades at a much more early stage than vibration analysis.

*2.1.5. Debris Monitoring.* Debris monitoring can be used to monitor the electrostatic and debris caused by blade rubbing. This method has been studied by Cartwright and Fisher [34] and Fisher [35]. In this technique, electrostatic sensors mounted in the turbine gas path were used to monitor the electrostatic charge that grows with blade rubbing. Besides, Powrie and McNicholas [36] also used this method to monitor the electrostatic charge and debris in the exhaust gas stream in order to detect blade rub and combustion chamber deterioration.

*2.1.6. Blade Tip Monitoring.* Optical measurement of blade vibration has been used for blade tip clearance monitoring by Simmons et al. [37]. This is done by installing an optical blade tip sensor at a spot on the blade surface. The probe of the fiber optic bundle will then image the spot. Any change in the distance between the blades tip and probe would cause the images spot on the fiber optic to move across the face of the bundle, and the distance is directly related to the change in blade to the probe. This method has been tested on an experiment rig and could be used to monitor blade tip clearance. This method can therefore be used to provide early detection of blade rubbing in gas turbine. Von Flotow et al. [38] used capacitance blade tip sensor to detect parameters such as the time of arrival and angle of arrival and thus provide information to detect various types of blade faults such as loss of blade, crack, rubbing, and bend blade. A powerful and reliable technique for blade tip clearance measurements that can be used under extremely harsh environments is presented by Steiner [39]. This method utilizes a heavy duty blade tip probe to detect shaft eccentricity or blade oscillations and thus provides information on the condition of blade. This method has also been studied by Sheard [40] among others.

*2.1.7. Temperature Monitoring.* In this method, blades running hotter than other blades can be detected and thus provide useful information for the prediction of creep. A blade temperature measurement system was also developed by Land Infrared Inc. This system is claimed to be capable of giving early warning of potential blade failures caused by overheating, such as creep. Annerfeldt et al. [41] presented a thermocrystal technique for monitoring the temperature of turbine blades and vanes. The technique was shown to be reliable and to have good accuracy in temperature gradients measurements. The study of heat transfer and stress distributions on a gas turbine blade was investigated by Kim et al. [42]. It was reported that the highest temperature on a turbine blade is located at the stagnation point of the blade leading edge. The point of maximum stress on a turbine blade is at its root. Turbine blade failures could therefore be estimated by monitoring the total stress resulting from combination of thermal load and cooling effects. A commercial online Thermal Barrier Coating (TBC) blade monitoring system has also been developed by Siemens Westinghouse Power Corporation Engineering in collaboration with Siemens Corporate Research [43]. The technique combines innovative access port design, high-speed infrared imagery, a tailor-made overall control and image evaluation system, and related TBC lifting models. The presented online technique is able to capture two-dimensional quantitative infrared images of row-1 blades during full engine operation and can help in not only ensuring the safe blades operation but also extending the blade's life.

*2.1.8. Performance Monitoring.* Performance monitoring involves the acquisition of a variety of data (temperature, pressure, and speed) located along the gas turbine and then calculating the performance of the parameters such as mass flow rate and compressor and turbine operating efficiency. Performance monitoring methods are a valuable tool to detect blade fouling and rotating stall. These faults usually will cause some aerodynamics distortion on blades and affect the overall performance of the machine. This method has been studied by Dundas [44], Dundas et al. [45], and Meher-Homji and Boyce [46] amongst others. An algorithm for blade fault diagnosis using hybrid method (performance and vibration monitoring) was developed by Kubiak et al. [47]. It is shown that by using this hybrid algorithm, blade faults such as the wearing-out effects of the blade and blade fouling could be detected. Table 1 provides a summary of the blade condition monitoring methods discussed in the proceeding section.

## 2.2. Advanced Signal Analysis Techniques

*2.2.1. Wavelet Analysis.* Aretakis and Mathioudakis [48] proposed a blade fault diagnostic method based on wavelet analysis. Wavelet analysis is performed on the time signals of the casing vibration, unsteady pressure, and acoustic measurements taken from commercial gas turbines. They highlighted that a distinctive difference could be seen from the wavelet map of healthy and faulty signals around BPF level. They have also demonstrated that each type of blade faults (fouled blade, twisted blade, and mistuned stator blade) could generate a unique signature of wavelet pattern based on the pressure signals. The authors investigated the feasibility of wavelet analysis for multistage blade faults diagnosis [49]. In another research paper [50] the current authors have also explored the usage of wavelet analysis for loose blade detection. Loose blade was found to be only detectable during the rotor coast-down process. Application of wavelet analysis in monitoring the different types of blade faults such as rub due to rotor eccentricity or creep has also been presented by the authors of [51]. It was showed that wavelet analysis can be used to reveal useful information about the blade condition and also to diagnose root cause of blade faults. Yuan et al. [52] used the wavelet analysis method to detect cracked turbine blades. It was demonstrated that both the Short Time Fourier Transform (STFT) and Mallat's wavelet transform could be used to obtain the characteristics of a cracked blade based on the high frequency impacts signals found on the STFT and Mallat's wavelet. Peng et al. [53, 54] reported on application of wavelet scalogram and wavelet phase spectrum to detect blade rubbing and rubbing-caused impacts. They have found that these techniques can be used to better detect rub impact

TABLE 1: Summary of blade condition monitoring methods.

| Blade monitoring methods | Monitoring parameters | Characteristics and applications |
| --- | --- | --- |
| Vibration | Blade pass frequency (BPF) | (i) Easy to implement<br>(ii) Suitable for blade rubbing detection<br>(iii) Not sensitive to detect minor faults such as blade geometry alterations |
| Pressure | Pressure distortion around blades | (i) Suitable for blade deformation and fouling detection<br>(ii) Difficult to deploy under operating conditions |
| Acoustic | Acoustic signal | (i) Suitable for blade rubbing detection<br>(ii) Sensitive to noise |
| Debris | Particle in oil and charges | Suitable for blade rubbing and FOD detection |
| Strain gauge | Displacement | Suitable for blade deformation and blade fatigue detection |
| Temperature | Temperature | (i) Suitable for blade creep monitoring<br>(ii) Can provide early warning<br>(iii) Embedded temperature sensors are required |
| Performance | Performance (efficiency, output, fuel consumption, etc.) | (i) Suitable for blade fouling and rotating stall detection<br>(ii) Large number of sensors required<br>(iii) Large number of data and calculation required |

signal as compared to FFT analysis. A blade fault diagnosis approach is also proposed by Qing-Yang et al. [55] by using the combination of the Morlet wavelet transform and neural network for feature recognition purpose. Wang et al. [56] also applied lifting wavelet transformation to detect blade faults. The current authors also studied the various applications of wavelet analysis technique [57, 58] to analyze vibration signal for blade rubbing detection.

*2.2.2. Artificial Intelligence and Pattern Recognition Techniques.* Probabilistic neural networks method was presented by Kyriazis et al. [59] to diagnose various types of blade faults. Angelakis et al. [60] proposed a method of using neural networks to diagnose blade faults in gas turbines. In his study, neural network-based fault diagnosis was used as pattern recognition tool to discriminate the patterns of faulty from healthy blades using signals measured from twelve different sensors or signals such as vibration and pressure signals. Loukis et al. [61] presented an automated blade faults detection method based on spectral pattern analysis technique. They have incorporated an innovative feature into a computer expert system to automatically detect and identify the type of fault in gas turbine by deriving the values of discriminants calculated from spectral patterns of fast response measurement signals such as casing vibration, internal pressure, and acoustic emission. It was found that blade fouling, blade twisting, and stator blade restaggering could be detected automatically based on this method. Aretakis et al. [62] presented a hybrid method to diagnose compressor blade fouling faults based on the combination of pattern recognition techniques known as the geometric and statistical pattern recognition technique. These pattern recognition techniques were shown to be viable to diagnose minor blade faults. Dedoussis et al. [63] presented a method based on the numerical simulation of blade fault signatures from unsteady wall pressure signals. This method produced the blade fault signatures of gas turbine using only theoretical computations. They employed a panel technique for the

calculation of the flow field around blade cascades. From the calculation, time waveform of the pressure signal at a location on the casing wall facing the rotating blades is developed. By processing the faulty time, waveform signal will enable the construction of the faulty spectra signatures. This method gives rise to the possibility of establishing the blade fault signatures without having to perform any experiments at all.

*2.2.3. Computational Fluid Dynamics (CFD).* Aretakis et al. [62] demonstrated the application of CFD to derive blade faults signatures. It was reported that this method can thus provide a basis for blade faults identification in gas turbine and compressors. Stamatis et al. [64] presented a study of blade faults diagnosis in gas turbine based on the CFD method. In this paper, a measured quantity was used as an input for physical modeling and the physical blade configuration is produced as the final output. This method provides a direct geometrical picture of the blade faults and does not rely on the interpretation of conventional fault signatures. Besides, Koubogiannis et al. [65] also used CFD method to create a database for gas turbine blade fault diagnosis solely based on signal modeling approach. They have shown that blade fault signature databases could be created without the need to conduct any costly experiments by using the method of unstructured and parallel CFD processing. CFD method was also investigated by Yokoyama et al. [66]. Hameed and Manarvi [67] also used CFD to predict crack locations at turbine blades surface.

*2.2.4. Statistical Analysis.* Romessis et al. [68] proposed the use of probabilistic reasoning to derive statistical information. It was showed that this method could be used to detect component faults (i.e., blade related faults) of jet engine. Loukis et al. [69] developed an automated method for gas turbine blade fault diagnosis based on the principals of statistical pattern recognition. The decision-making feature is based on the derivation of spectral patterns from dynamic
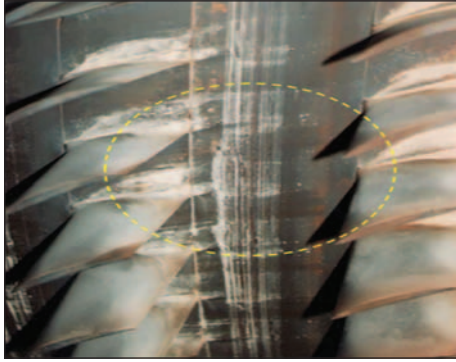
Figure 1: Marks of blade rubbing on compressor rotor.

measurement data. The calculations of discriminate coefficients with respect to the reference spectral patterns of the faults were done by taking into account their statistical properties. In this method, the success rate of automated decision making is further improved, and the need for intuitive discriminate selection is eliminated. Zhang et al. [70] presented a signal recognition method to recognize the blade fault based on the symmetry and similarity principal by making use of the means, variance, and means of variance to eliminate the effect caused by the parameter differences between blades. The plotting of means of variances showed that it can be used to distinguish the faulty from the healthy blade.

## 3. Condition Monitoring of Different Types of Blade Faults

In this section, the most frequently occurring blade faults in turbomachinery are categorized into five types, namely, blade rubbing, blade fatigue failure, blade deformation (twisting, creeping, corrosion, and erosion), blade fouling, and loose blade. A review of the most suitable method to detect each type of blade faults is presented in the following section.

*3.1. Blade Rubbing.* The occurrence of blade rubbing in turbomachinery has become more prevalent with the advent of high performance turbomachinery design. This is because the primary design consideration of these machines is to minimize the operational clearances between rotating blades and casing in order to increase cycle efficiencies and thus reduce the overall fuel consumption [71]. According to Barschdorff and Korthauer [23], blade rubbing and blade fatigue failure were reckoned to be the most prevalent blade faults in gas turbine with 23% of total blade failures in gas turbines contributed by rubbing whist 18.5% by blade fatigue failure (i.e., crack, loss of part, and FOD). The consequences of blade rubbing could be very serious as it can lead to other more destructive failures in machinery such as FOD due to broken blade parts. Figure 1 illustrates the effect of blade rubbing on the surface of compressor rotor.

To date, abundance of studies have been conducted to understand the effects and mechanisms of blade rubbing

in turbomachinery. Choy and Padovan [72] investigated the characteristics of the nonlinear dynamics of rubbing and have established the relationship of various parameters of rubbing excitation such as the relationship of rub force and energy levels with rubbing duration and incidence separation angles. Laverty [73] studied the mechanics of rubbing between a compressor blade tip seals and rotor casing. He found that the total energy of rubbing is mainly contributed by the incursion rate of the rubbing as compared to rubbing velocity and the thickness of the blade. He concluded that the overall rubbing energy increased in proportion to the quantity of blades that are involved in the process of rubbing. Sawicki et al. [74] studied the dynamic behavior of rotors rubbing and found that the vibration spectrum of rubbing is mainly dominated by subharmonic, quasiperiodic, and chaotic vibration components. Ahrens et al. [75] conducted an experimental study to investigate the resulting contact forces (in radial and tangential direction) during the process of rubbing. Roques et al. [76] formulated a mathematical rotor-stator model of a turbogenerator in order to study the speed transients and angular deceleration associated with rubbing. These reports, amongst others, have provided a deeper understanding of the mechanics and mechanisms of rubbing and thus enabled a better interpretation of rub related observations and signals in relation to their actual physical condition that occurred. Blade rubbing detection in turbomachinery is often accomplished by establishing the vibration symptoms of rubbing from time domain (i.e., vibration waveform, orbit plot), frequency domain (i.e., FFT), and also time-frequency domain (i.e., wavelet and STFT) signal analysis. A literature review by Muszynska [77] provided exhaustive information related to vibration, rotor dynamics, and the resulting rotor orbit during rubbing. This information could be used as a reference to detect blade rubbing in turbomachinery. Kubiak et al. [78] highlighted that blade rubbing could be detected if the blade passing frequency (BPF) amplitude is found to be exceptionally high in the vibration spectrum. Beside this, the presence of the abnormal frequency harmonics peaks (2x, 3x, 4x, etc.) of the operating speed in the vibration spectrum could also indicate the occurrence of blade rubbing. A drastic escalation in rotor subharmonic peaks in the vibration spectrum could also infer the presence of blade rubbing as reported by Meher-Homji [79]. Patel and Darpe [80] studied the early detection of rubbing in turbomachinery based on the vibration signal measured during a coast-up of a machine. They found that the Hilbert-Huang signal analysis could be applied to detect early rubbing in a rotor system based on the vibration signal measured during the coast-up of a machine. Wavelet analysis method was also widely used to detect rubbing in turbomachinery. For instance, Peng et al. [54] conducted a study to determine the effectiveness of using the conventional scalograms as compared to the reassigned scalograms for the detection of rubbing. They found that when rubbing occurred, its rubbing impacts could lead to an increase in vibration amplitude at high frequency region. They concluded that the vibration amplitude peaks of high frequencies region increase in correspondence with the increase of severity of rubbing. Wang and Chu [81] proposed a method to determine the location of rubbing

in a rotor bearing system based on acoustics emission and wavelet analysis. Peng et al. [82] used wavelet analysis as a means for feature extraction of rubbing impact signal in a rotor system. Hee and Leong [83] conducted an experimental study to understand the dynamic responses of casing deflection profile due to different configurations of blade rubbing and found that the detailed analysis of amplitude and phase angle of the casing vibration could be used for blade rubbing classification. Leong and Lim [84] proposed a method that involved wavelet analysis technique to detect blade looseness and monitoring blade pass frequency signals for blade rubbing and cracks identification. Cong et al. [85] reported the use of an impact energy model for the evaluation of rotor rub impact fault where spectrum analysis can show a distinctive pattern for different severity states of the blade rub.

Besides vibration analysis, acoustic emission method was also proposed by Mba and Hall [86] to detect blade rubbing. They found that the stress waves and acoustic emission produced during the frictional rubbing process can propagate across the turbine surface and across the bearing interface allowing measurement to be made by the sensor attached to bearing housing. Meher-Homji [87] commented that the simple acoustic measurement could also be used to detect blade rubbing using stethoscopes during gas turbine startup and shutdown and this technique has already been adopted by gas turbine operator. Fisher [35] commented that many techniques such as the performance and vibration monitoring are dependent on a secondary effect being produced by the rubbing fault. For instance, blade rubbing can only be detected by these techniques provided sufficient material loss has occurred and results in an imbalance or loss of performance. He has adopted an engine distress monitoring system (EDMS) to monitor in real time the debris produced by the gas path component, such as blade rubbing and combustor faults. He has found that this method is capable of providing a more direct indicator of blade rubbing as the measurement made based on the actual debris produced by the fault probably before remedial action is required, thus giving a sufficient prognosis period. Simmons et al. [37] presented a method for blade tip clearance monitoring using an optical probe and found that this method could provide early indication of a blade rubbing if the measured blade tip clearance has reduced considerably.

### 3.2. Blade Fatigue Failure (Crack, Loss of Part, and FOD).
Blade fatigue failures in turbomachinery are generally caused by high and low cycle fatigue of the blades. High cycle fatigue in turbine blades is often caused by aerodynamic excitations or self-excited vibration (flutter). High cycle fatigue damage occurs when stress levels are above its fatigue strength. In contrast, low cycle fatigue occurs as a result of frequent start-stop cycle of a machine which can lead to crack in bores and bolt hole areas of compressor and turbine disks that operate under high centrifugal stress. In this situation, a minute flaw could grow into crack which upon attaining critical size could result in total rupture of blade. In addition, crack can also be caused by resonant fatigue in blade.

Resonant fatigue is an important failure mechanism which arises when a periodic force acts at a frequency corresponding to a blade natural frequency. If the damping is inadequate, crack will eventually develop and propagate and total blade failure could occur as commented by Meher-Homji [87]. A nonintrusive measurement method for measurements of torsional vibration signals for blade crack detection was also studied by Maynand and Trethewey [88–90].

It is well understood that any damage in turbine blades, including cracks, can cause shift in blade's resonance frequencies. Therefore the monitoring of the blade resonance condition is often adopted to detect a crack in blade. Lackner [91] presented a crack detection method for compressor blades in gas turbine engine using eddy current sensors. He observed that crack in blade was found to lower the resonant frequency of the first torsion mode of the blade. Mercadal et al. [21] employed a method using a noncontacting stress monitoring system to monitor blade resonance condition. Various methods of nondestructive testing such as eddy current and ultrasound were also often used to detect crack in turbine blades. Telemetry measurement method to monitor direct blade vibration was also used and studied by Scalzo et al. [20] and Mercadal et al. [21]. However, the methods of monitoring blade vibration using eddy current and strain gauge seem to be only applicable during machinery outage condition.

Vibration analysis is often employed in the field to monitor health condition of turbomachinery. However, vibration analysis is only capable of detecting fatigue blade failure if there is massive loss of blade part that could cause the changes in rotor dynamics characteristics of the machine. Meher-Homji [87] presented a case study whereby severely damaged first-stage turbine blades could not even show up in its vibration spectrum. Doftman and Moroslav [92] presented in their paper that a crack at the turbine blade root could be caused by the fatigue initiated by the rotor torsional vibration. Torsional vibration is generally a sporadic, transient phenomenon provoked by a sudden load change on the grid. Hence, the measurement and monitoring of the torsional vibration could be used to provide early warning for crack at turbine blade root. This method was also studied by Maynard and Trethewey [93].

### 3.3. Blade Deformation (Creep, Twisting, Erosion, and Corrosion).
Blade deformation in turbomachinery could occur due to creep, erosion, corrosion, and FOD induced blade twisting. Figure 2 depicts photographs of compressor blade deformation. Generally, blade deformation could cause obstruction in the flow of a machine and therefore could be detected by measuring the pressure field around the blades. This method has been proposed by Mathioudakis et al. [13] and Dedoussis et al. [63]. As shown by Aretakis and Mathioudakis [48], the distortion of pressure signals around the blades could indicate the occurrence of twisted blade. Beebe [94] also commented that the erosion of the blade due to the solid particles could also be detected using the performance monitoring method when gas turbine efficiency has dropped substantially. Beside this, a technology developed by GE power system known
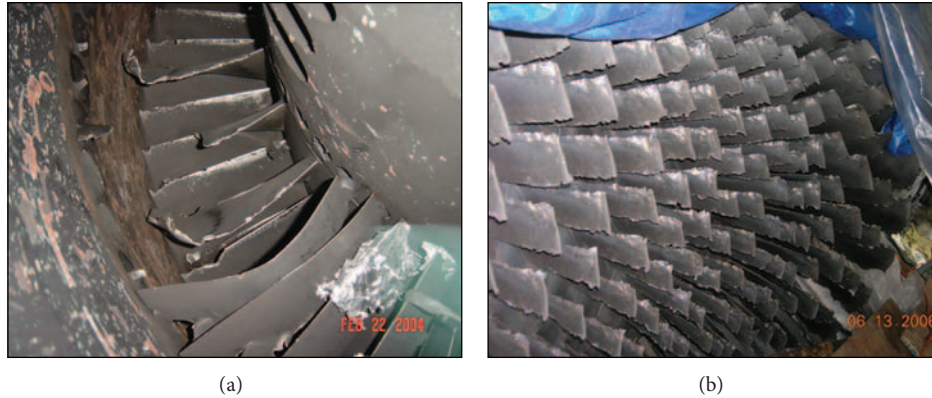
(a)


(b)

FIGURE 2: Photographs of blade deformation.

as taggant coating system can be used to detect any blade corrosion or erosion of blade. Any detection of the coated material at exhaust collector can be used as the indication of the presence of corrosion and erosion of the Mann [95].

*3.4. Blade Fouling.* Blade fouling is an important mechanism leading to performance deterioration in turbomachinery over time. Kurz et al. [96] explained that fouling is normally caused by the adherence of particles to airfoils and annulus surfaces. A case study of the causes and effects of fouling on gas turbine operation can be found in Meher-Homji [97, 98]. He found that compressor blade fouling could be detected based on performance monitoring method. The solids or condensing particles in the air and combusted gasses could precipitate on the rotating and stationary blade, thus causing some changes to the aerodynamic profile and invariably dropping the compressor mass flow rate and affecting the turbine flow coefficient. Therefore the dropping of the overall power output and thermal efficiency of the gas turbine could indicate the presence of the fouled blade. Mathioudakis et al. [13] presented that the measurement of the pressure field around rotating blades in turbomachinery is a more sensitive method as compared to performance monitoring to detect fouled blade. However, pressure monitoring method is difficult to be applied for gas turbine and compressor during actual operation.

*3.5. Loose Blade.* Loose blade in turbomachinery is a special condition whereby it usually involves not only the blade itself but also the mechanism of blade locking or blade attachment design. The authors Lim and Leong [50] have encountered a loose blade condition in one of the power stations in Malaysia. An experimental study of loose blade found that loose blade is not detectable under normal operation condition due to centrifugal force. Instead, it can only be detected during rotor coast-down stage by observing the impactive signals caused by the loose blade. Beside this, Kuo [99] also conducted a study on the diagnosis of the loose blade with Fourier's analysis method on vibration signal. He used neural networks and fuzzy logic methods to develop

a pattern recognition algorithm to enhance the detection of loose blade using vibration analysis.

## 4. Conclusion

Blade faults remain as one of the most elusive and frequently occurred faults in turbomachinery. The selection of blade monitoring method depends largely on the characteristics of blade faults as well as the practicality of the measurement itself. In summary, vibration analysis and BPF method can be used effectively for the detection of severe blade rubbing. For minor or early blade faults detection, pressure measurements, blade tip monitoring, acoustic emission, and debris monitoring should be used in lieu of vibration measurements. For the detection of blade fatigue failures, strain gauge measurements and blade vibration monitoring methods can be used to monitor any change in blade resonance frequency. For blade deformation and blade fouling detections, performance monitoring was found to be the most effective method available to date. This paper aims to provide an overview of the most feasible approaches for condition monitoring of blade in turbomachinery.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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