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COMPRESSORS AND MODERN PROCESS APPLICATIONS

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Preface

Compressors represent a multimillion dollar investment for many plants, and profitability can be neither reached nor sustained by organizations that neglect this critically important asset. This is clearly brought out in more detailed compressor texts; these are available and listed in the references. However, whereas these more detailed texts have often been recommended for and by machinery reliability professionals, a condensed overview of compressor design, operation, and maintenance is desired by other job functions and will thus be given in this book. This material will assist the very wide spectrum of readers whose process involvement brings them into contact with large process compressors. As an example and to run a smooth organization, terminology must be unified and misconceptions dispelled wherever they creep into our thinking.

Editor

Contents

Chapter 1

Pressure Pulsation Signal Analysis for Centrifugal Compressor Blade Crack Determination

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ABSTRACT

Blade is a key piece of component for centrifugal compressor. But blade crack could usually occur as blade suffers from the effect of centrifugal forces, gas pressure, friction force, and so on. It could lead to blade failure and centrifugal compressor closing down. Therefore, it is important for blade crack early warning. It is difficult to determine blade crack as the information is weak. In this research, a pressure pulsation (PP) sensor installed in vicinity to the crack area is used to determine blade crack according to blade vibration transfer process analysis. As it cannot show the blade crack information clearly, signal analysis and empirical mode decomposition (EMD) are investigated for feature extraction and early warning. Firstly, signal filter is carried on PP signal around blade passing frequency (BPF) based on working process analysis. Then, envelope analysis is carried on to filter the BPF. In the end, EMD is carried on to determine the characteristic frequency (CF) for blade crack. Dynamic strain sensor is installed on the blade to determine the crack CF. Simulation and experimental investigation are carried on to verify the effectiveness of this method. The results show that this method can be helpful for blade crack classification for centrifugal compressors.

INTRODUCTION

With the development of the society, centrifugal compressor has been widely used in modern industry such as petroleum, chemicals, metallurgy, and aerospace field as an important fluid machine [1]. Meanwhile, centrifugal compressors are developing to be large in scale, high in speed, and automatic in operation [2]. However, the blade failure usually emerges. As the most important part, the impeller transforms kinetic energy into pressure energy. But the impeller suffers from the effect of centrifugal forces, gas pressure, and friction force which usually lead to cracks. According to statistical analysis, 65% centrifugal compressor malfunctions are closely related to the blades. In addition, 40% blade fatigue failures are not fully understood so far [3]. Examples of blade cracks are shown in Figure 1. Fluid-induced vibration is an important factor for blade fatigue failures. It contains acoustic resonance, unsteady flow, rotating stalls, and flutter [4, 5]. Due to the high-velocity flow through the centrifugal compressor and rotating impeller, high-pressure fluctuations occur in the cavity of compressor which could lead the impeller to irregular vibration. Pressure fluctuation acts on the impeller, leading to stress convergence and cracks in the blades. The growing crack will cause blade failure, which results in catastrophes.

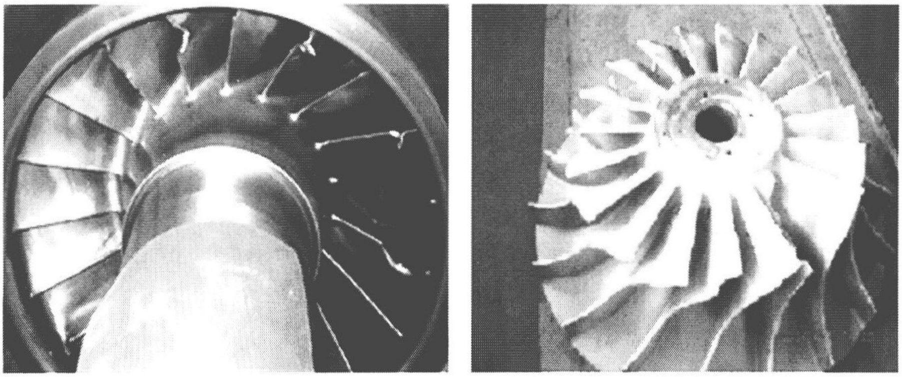

Figure 1: Pictures of centrifugal compressor blade cracks.

There are many reasons for cracks on the blades of compressor. Blade cracks are mainly associated with the detection of material, production process, working condition, and high cycle fatigue. So far, researches were mainly concentrated on the defects in the material, processing, and manufacture of impeller causing high fatigue failure. Lourenço investigated the failure of blades [6]. Kermanpur et al. analyzed the failure mechanism of compressor blades made of Ti6Al4V. The results showed fretting fatigue mechanism is the main cause of several premature failures of Ti6Al4V alloyed compressor blades [7]. In recent years, blade cracks caused by excessive alternating stress induced by air-excited vibration have drawn more and more attention from the researchers. In 2007, Eisinger studied the acoustic fatigue which is the coincidence of impeller structural and cavity acoustic modes. The results indicated that the acoustic fatigue would significantly increase the amplitude of vibration and damage the blades [8]. Investigation on alternating stress can be helpful to prevent or reduce the damage from blade cracks [9]. Therefore, condition monitoring and pattern classification are important to prevent blades from failure as well as blade crack detection which could ensure safe operation of the compressor.

It is well known that blade cracks will result in breakdown or even serious accidents of the whole set for centrifugal compressor. It can even lead to heavy losses for a factory. Moreover, personal safety must be considered because the tangential velocity of breakdown blade can be up to 450 m/s. Therefore, incipient classification of blade crack becomes more and more important than ever before.

Traditionally, displacement sensors are introduced to monitor shaft vibration. Meanwhile, vibration-based condition monitoring is also used in shaft crack classification [10, 11]. But it is difficult to recognize shaft cracks only by vibration signals. Moreover, it is impossible to provide any information to characterize blade crack condition from the shaft vibration signals, making blade crack classification more difficult than shaft crack identification. Different methods for blade condition classification have been investigated by many researchers. Liu et al. studied the malfunction identification method of fan blade crack classification by using wavelet packet analysis [12]. Though the structure is similar to centrifugal compressor and fan, centrifugal compressor has good stiffness as the typical difference. Rama Rao and Dutta studied blade crack condition classification for gas turbine blade recognition by using vibration signal information [13]. Yang et al. proposed the auditory spectrum feature extraction using the support vector machine to identify the malfunction of fans [14]. Witek studied the experimental crack propagation for gas turbine blades via vibration signals in laboratory but it was not in a close-loop test-rig [15]. At the same time, some researchers studied wind turbine blade crack classification by using wavelet analysis, scalogram, and so on [16–18]. But it is different from centrifugal compressor blade working condition in speed and load. All these investigations are helpful for blade crack classification, but further study for early warning of centrifugal compressor blade is required. At the same time, air flow experiment is more important for blade condition analysis in real working conditions.

Pressure pulsation (PP) generated by the interference between rotating blades and the stationary vanes contains much information about the blade working conditions and has been used for blade status conditions analysis [19]. However, the crack information in PP signal is weak, so it is difficult to identify patterns just according to time or frequency information, especially for the incipient blade crack condition. Further feature extraction methods are urgently needed for better information collection. Empirical mode decomposition (EMD) is an effective tool for nonstationary signal analysis, which has been widely applied in rolling element bearings and gearbox fault diagnosis. It has great advantage and adaptability in the mechanical fault diagnosis and feature extraction. EMD is a new time-frequency signal analysis method proposed by the scientist of National Aeronautics and Space Administration (NASA) Huang et al. in recent years [20]. This method has been broadly investigated by many researchers since it was provided. It has been applied in different areas for fault diagnosis. Parey et al. used EMD statistical method to detect incipient fault of the gears [21]. Loutridis applied the instantaneous energy density and EMD to monitor and diagnose the gear fault [22]. Liu et al. detected the gear incipient fault with EMD and they found that the result was better than that of wavelet decomposition [23]. EMD can also be used in machine fault diagnosis based on concrete analysis of specific issues. The vibration of blade crack generates a characteristic frequency (CF) which can be modulated into blade passing frequency (BPF). Therefore, EMD can be applied to determine the CF of blade cracks despite of the noise interference in practical working centrifugal compressor. It is also similar to gearbox fault diagnosis problems.

In this paper, PP signals are used for blade working condition classification by using EMD. Experiments are carried on to verify the effectiveness of this method in a test-rig. To verify the effectiveness of this method, strain testing is also carried on for the blade crack analysis. The structure of this paper is as follows. Section 2introduces the theory of feature extraction for blade crack classification. Section 3 presents the simulation signal analysis. Section 4 describes our experimental setup for blade crack monitoring. Section 5 demonstrates PP signal analysis for blade condition classification. Section 6 gives concluding remarks.

THEORY AND METHOD

Empirical Mode Decomposition

EMD is developed based on instantaneous frequency calculation. It has been considered a very useful tool for the analysis of nonstationary and nonlinear signals [20]. For an arbitrary time series X(t), it can decompose the original into many narrow-band components, each component known as intrinsic mode functions. An intrinsic mode function is used to convert it into a practically useful instantaneous frequency. The intrinsic mode function satisfies two conditions: (1) in the whole range of a data set, the number of the extreme must be equal to the number of the zero crossing points or the difference between them must be one; (2) at any given time, the mean value of the local positive extreme is equal to that of the local negative extreme. An arbitrary nonstationary and nonlinear signal can be decomposed into a series of components satisfied with the intrinsic mode function by using the local wave decomposition method. It is a sifting process and can be written as

$$\begin{aligned} X(t) - C_1(t) &= r_1(t) \\ r_1(t) - C_2(t) &= r_2(t) \\ &\vdots \\ r_{n-1}(t) - C_n(t) &= r_n(t). \end{aligned} \tag{1}$$

The original data can be decomposed into an n-series of intrinsic mode components plus a residual component r_n. The residual can be either a variable or a constant. Thus, the original signal can be expressed as

$$X(t) = \sum_{i=1}^{n} c_i(t) + r_n(t). \tag{2}$$

After EMD, intrinsic mode function (IMF) can be obtained. FFT can be used on different IMFs analysis for CF determination. EMD can be looked as a filter on feature determination. Therefore, it is helpful to obtain the CF.

Blade Characteristic

In general, centrifugal compressor casing vibration and radiation noise are closely related to blade BPF and its harmonics. It is also generated by the interference between rotor and stator during blade high speed rotation. BPF has high energy in the pressure frequency spectrum. It is the main source of centrifugal compressor noise. Its value can be determined by shaft speed multiplying the number of blade. BPF can be calculated by

$$\mathrm{BPF} = \frac{\mathrm{RPM}}{60} \times N, \tag{3}$$

where RPM is the shaft speed and N is the number of blades on the impeller.

BPF is the interference between rotator and stator. As BPF is a high frequency component, the low frequency components for blade nonorder vibration can be modulated to BPF during rotation. The modulation information will appear as the sideband frequency of the BPF. For unbalanced rotor conditions, SF will also be modulated to the BPF giving a sideband frequency around the BPF for unbalanced condition. Sideband frequency could be used to determine the modulated CF. The sideband frequency produced for blade cracks is different from SF. It can be used to warn blade crack. It does not mean that there is a blade with cracks if SF is the sideband frequency for BPF. It is also difficult to classify CF just according to the spectrum for the incipient crack as the magnitude of the blade vibration is weak compared with the amplitude of BPF. Therefore, effective feature extraction is urgently needed for blade crack analysis.

Blade Crack Characteristic Frequency Determination

The steps for CF determination are shown in Figure 2. Firstly, PP is monitored based on the best suitable position according to blade crack classification. This is also a key step to determine the crack information because the sensor location has a direct effect on classification accuracy. Secondly, band-pass filter is applied on signal analysis. Envelope analysis is used to filter BPF signal. Then, IMFs can be obtained by using EMD. Fast Fourier transform is used on different IMFs. In the end, CF for blade crack can be obtained. Blade strain is used to verify the effectiveness of this method.

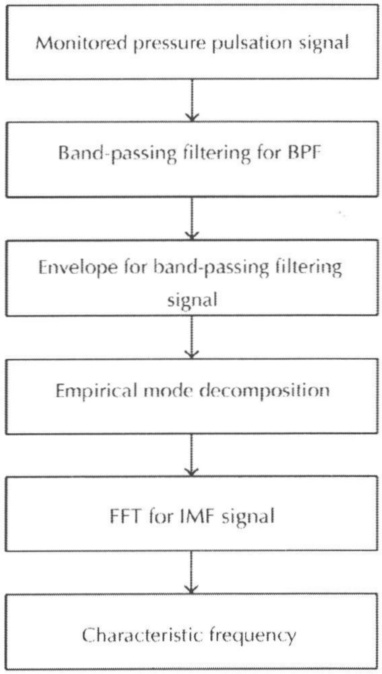

Figure 2: Flowchart for blade crack classification using PP signal.

SIMULATION SIGNAL ANALYSIS

For a amplitude modulation signal sig(t), it can be expressed as

$$\mathrm{sig}(t) = A\left(1 + B\cos\left(2\pi F_e t\right)\right)\sin\left(2\pi F_c t\right), \tag{4}$$

where, F_c=1500 Hz, F_e=10 Hz, A=60, and B=0.3. F_c and F_e correspond to carrier frequency and modulation frequency, respectively. The corresponding sampling frequency is 10,240 Hz for the simulation signal. Based on (4), an amplitude modulation signal can be obtained as shown in Figure 3(a). Fourier spectrum analysis is shown in Figure