

An Overview on Vibration Analysis Techniques for the Diagnosis of Rolling Element Bearing Faults

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Abstract— Rolling element bearings comes under the critical category in many rotating machineries, mainly in chemical industry, aviation, nuclear power stations etc. Vibration monitoring and analysis is useful tool in the field of predictive maintenance. Health of rolling element bearings can be easily identified using vibration monitoring because vibration signature reveals important information about the fault development within them. Numbers of vibration analysis techniques are being used to diagnosis of rolling element bearings faults. This paper attempts to summarize the recent research and developments in rolling bearing vibration analysis techniques. Bearing defects and bearing characteristic frequencies (BCF) are also discussed.

Keywords—Rolling Element Bearing, Vibration, Bearing Fault, Vibration Analysis, Fault Diagnosis.

I. INTRODUCTION

Rolling element bearings are mostly used in rotating machineries and consider as a most critical component. Proper functioning of bearings is most important in nuclear power stations, chemical plants, aviation industries and also process industries. A large survey on faults in the electric motor was carried out by Electric Power Research Institute (EPRI) in 1985 and found that 41% of faults related to worn motor bearings [1]. Well performance and reliability of rolling element bearings is essential for proper functioning of machines and to prevent catastrophic failure of the machinery. Bearing health and performance can be easily identified by using health monitoring techniques. Many condition monitoring techniques is available to monitor the health of bearing; these are wear debris analysis, motor current analysis, noise monitoring, temperature monitoring, vibration monitoring etc. But the vibration monitoring is the most useful technique because it is reliable and very sensitive to fault severity. Bearings act as a source of vibration and noise because of either varying compliance or the defects presence in parts of bearing. These vibration signals will give us information about the health of bearing. Vibration

monitoring is the most popular technique to diagnosis of rolling element bearing faults.

Many researchers have been worked on vibration signal analysis techniques and numbers of research papers have been published by them. Review papers have also been published by researchers on bearing defects diagnosis techniques. In 1983, Kim and Lowe [2] reviewed vibration and wear debris analysis techniques in a particular reference to railway freight car. McFadden and Smith [3] reviewed the vibration monitoring of rolling element bearing by High-Frequency Resonance Technique. A detailed review on vibration and acoustic monitoring techniques for detection of defect in rolling element bearing presented by Tandon and Nakra [4] in 1992; they covered vibration measurements in time and frequency domain, sound measurement, shock pulse method and acoustic emission techniques in this review. Tandon and Choudhury [5] presented a review on vibration and acoustic measurement methods for the detection of defects in rolling element bearings; they covered vibration measurement in both time and frequency domains along with high-frequency resonance technique and for acoustic measurements sound pressure, sound intensity and acoustic emission techniques other then this they also included wavelet transform method and automated data processing technique. The aim of this study is to include the recent research and developments in the vibration analysis techniques for diagnosis of rolling element bearings faults.

II. BEARING DEFECTS

The defects in the rolling element bearings may arise mainly due to following reasons such as; improper design of the bearing or improper manufacturing or mounting, misalignment of bearing races, unequal diameter of rolling elements, improper lubrication, overloading, fatigue, uneven wear etc. The rolling element bearing defects/faults classified into two categories; distributed defects and localized defects.

A. Distributed Defects

Distributed defects are mainly caused by manufacturing error, inadequate installation or mounting and abrasive wear [6]. Distributed defects include surface roughness, waviness, misaligned races and unequal diameter of rolling elements [7]-[8]. The change in contact force between roiling elements and raceways due to distributed defects cause an increased in the vibration level. Hence, the study of vibrations generated by distributed defects is mainly for quality inspection of bearings as well as for condition monitoring [9].

B. Localized Defects

These defects include cracks, pits and spalls on rolling surfaces caused by fatigue [10]. The common failure mechanism is the crack of the races or rolling elements, mainly caused when a crack due to fatigue originated below the metal surface and propagated towards the surface until a metal piece is detached causing a small defect or spall [5]. This defect accelerate when the bearing is overloaded or subjected to shock (impact) loads during their functioning and also increase with the rotational speed. Spalling can occur on the inner ring, outer ring, or rolling elements.

III. BEARING CHARACTERISTICS FREQUENCIES

A machine with a rolling element bearing is running at certain speed; now a defect begins to develop, the vibration spectrum changes produced in bearing. The occurrence frequencies of the shocks resulted from the defects in the bearings are called bearing defect frequencies or bearing characteristics frequencies. Each bearing element has a bearing characteristic frequency. The peaks will occur in the spectrum at these frequencies due to increase in vibrational energy. Initiation and progression of defects or faults on rolling element bearing generate specific and predictable characteristic of vibration. A model presented by Tandon and Choudhury [7], [11] predicted frequency spectrum having peaks at these frequencies. Defects in components of rolling element bearing such as inner race, outer race, rolling elements and cage generate a specific defect frequencies calculated theoretically from the below equations:

- (a). FTF - Fundamental Train Frequency (frequency of the defected cage):

$$f \text{ (Hz)} = \frac{1}{2} S \left[1 - \left(\frac{BD}{PD} \cos \beta \right) \right] \dots \dots \dots (1)$$

- (b). BPFI - Ball Pass Frequency of the Inner race (frequency produce when the rolling elements roll across the defect of inner race):

$$f \text{ (Hz)} = \frac{n}{2} S \left[1 + \left(\frac{BD}{PD} \cos \beta \right) \right] \dots \dots \dots (2)$$

- (c). BPFO – Ball Pass Frequency of Outer race (frequency produce when the rolling elements roll across the defect of outer race):

$$f \text{ (Hz)} = \frac{n}{2} S \left[1 - \left(\frac{BD}{PD} \cos \beta \right) \right] \dots \dots \dots (3)$$

- (d). BSF – Ball Spin Frequency (circular frequency of each rolling element as it spins):

$$f \text{ (Hz)} = \frac{PD}{2 * BD} S \left[1 - \left(\frac{BD}{PD} \cos \beta \right)^2 \right] \dots \dots \dots (4)$$

- (e). Rolling Element Defect Frequency or 2 x BSF

$$f \text{ (Hz)} = \frac{PD}{BD} S \left[1 - \left(\frac{BD}{PD} \cos \beta \right)^2 \right] \dots \dots \dots (5)$$

Where:

- S=Speed (revolutions per second)
- n= No. of rolling elements
- β= contact angle (degrees)
- BD=ball or roller diameter
- PD=pitch diameter

The assumption made that there is no sliding and only pure rolling contact between the rolling elements and the races but in reality there exist some sliding. If there is sliding contact between rolling elements and the races the actual characteristics defect frequencies slightly different from the calculated [12], but mostly dependent on speed of the shaft, the type of fits and type of bearing.

IV. VIBRATION ANALYSIS TECHNIQUES

There is several vibration analysis techniques used to analyse the bearing vibration. In this paper, vibration analysis techniques are classified in four categories: time domain, frequency domain, time-frequency domain and other techniques.

A. Time Domain Techniques

Time domain technique is easiest and simplest technique to analyze the vibration signal waveform. Peak-to-peak amplitude is measure from the top of the positive peak to the bottom of the negative peak. Root mean square (RMS), measures the overall level of a discrete signal.

$$RMS(x) = \sqrt{x_i^2 / N} \dots \dots \dots (6)$$

Where, N is the number of discrete points and represents the signal from each sampled point. The resultant RMS values are compared with recommended values to determine the condition of a bearing [13]; however, this method is not sensitive to detect small or early-stage defects [14]. The crest factor is the ratio of peak acceleration over RMS. Ingarashi et al. [15] has reported that the value of the crest factor for good bearing is approximately five. At advance stages of material wear, bearing damage propagates, RMS increases, and crest factor decreases. Kurtosis is another important parameter to identify the health of bearing. The equation to calculate the value of kurtosis is given by:

$$k = \frac{\sum_{n=1}^N [x(n) - \mu]^4}{N \cdot (\sigma^2)^2} \dots\dots\dots (7)$$

Where, x(n) is the time series, μ is the mean value of the data, σ is the variance of the data and N is the total number of data points. A good surface finish bearing has a theoretical kurtosis of 3, and when the surface finish deteriorates value of kurtosis increases, but kurtosis is insensitive to loads and speeds [16].

Kurtosis value, Crest factor, Impulse factor and Clearance factor are non-dimensional statistical parameters. Impulse and Clearance factors have similar effects like Crest factor and Kurtosis value [17]. Li and Pickering [18] proved that the Impulse factor, Kurtosis value, Crest factor and Clearance factor are all sensitive to incipient fatigue spalling. Karacay and Akturk [19] investigated that the peak-to-peak value, RMS, Crest factor and kurtosis are only shows the damage at the ball bearing but do not give information about the location of defect e.g. inner race, outer race, cage or the roller.

B. Frequency Domain Techniques

Frequency domain, or spectral analysis, is the most popular approach for the diagnosis of bearing faults. Frequency-domain techniques convert time-domain vibration signals into discrete frequency components using a fast Fourier transform (FFT). Simply stated, FFT mathematically converts time-domain vibration signals trace into a series of discrete frequency components. The Fast Fourier Transform (FFT) is an algorithm for calculation of the Discrete Fourier Transform first published in 1965 by J.W.Cooley and J.W.Tuckey [20]. In a frequency spectrum plot, the X-axis is frequency and the Y-axis is the amplitude of displacement, velocity, or acceleration. The main advantage of frequency-domain analysis over time-domain analysis is that it has ability to easily detect the certain frequency components of interest. James Taylor [21] well explained the sequence of appearing and disappearing of peaks in the spectrum. The detailed knowledge of bearing characteristics frequencies (see section-III) required to identify the location of defect in rolling element bearing. Power

spectrum is used to identify the location of rolling element defects by relating the characteristic defect frequencies to the major frequency components which can be found in the spectrum. Power cepstrum is important bearing fault detection technique and it is defined as the inverse Fourier transform of the logarithmic power spectrum. A modified cepstrum analysis was proposed by Merwe and Hoffman [22].

Envelope analysis or amplitude demodulation is another popular technique used to detecting incipient failure of rolling element bearing. This method is also known by different names such as high frequency resonance technique [23]-[26], amplitude demodulation [27], demodulated resonance analysis and narrow band envelope analysis [28]-[29]. Envelope analysis or amplitude demodulation is the technique that can extract the periodic impacts from the modulated random noise produced within a deteriorating rolling element bearing. This process even possible when the signal from the rolling element bearing is relatively low in energy and ‘buried’ within the other vibrations produced from the machine.

Consider a defect on any element in a rolling element, when the rolling element or other surface in the bearing passes over this defect produces impulse or impact of very short duration. The energy of this impact is distributed at low level over a wide range of frequencies due to that identification of bearing defect is difficult to detect by the normal spectrum in the presence of vibration from the other machine elements. This impact excites the natural frequency of the bearing element resulting in the increase in vibration energy at a much higher frequency than the vibration generated within other machine element. In envelope spectrum, periodic impacts show up as a peak (with some harmonics) at the characteristics defect frequency corresponding to the faulty bearing element. Each bearing element has a characteristics defect frequency and it can be calculated theoretically as discussed before in section-III. Envelope analysis is a well-defined technique for bearing defect diagnosis. The efficiency of this technique has been evaluated by several researchers [23]-[24], [28]-[33]. Hilbert transform is an important tool in envelope analysis. It has also been used for machine fault detection and diagnostics [34]-[35].

A self-adaptive Noise Cancellation (SANC) technique gives better result with in conjunction to an envelope detection method has demonstrated by Ho and Randall [35]. Spyridon and Ioannis [36] studied vibration signals of the radial ball bearings which was loaded in radial direction and compared the results taken from FFT and envelope analysis and conclude that bearing fault can be easily found by using FFT where as envelope analysis is tool for detection of the bearing failure.

C. Time-Frequency Domain Techniques

Time-frequency domain techniques have capability to handle both, stationary and non- stationary vibration signals. This is the main advantage over frequency domain techniques.

Time–frequency analysis can show the signal frequency components, reveals their time variant features. A number of time-frequency analysis methods, such as the Short-Time Fourier Transform (STFT), Wigner-Ville Distribution (WVD), and Wavelet Transform (WT), have been introduced. STFT method is used to diagnosis of rolling element bearing faults [37]. The basic idea of the STFT is to divide the initial signal into segments with short-time window and then apply the Fourier transform to each time segment to ascertain the frequencies that existed in that segment. The advantage of wavelet transform (WT) over the STFT is that it can achieve high frequency resolutions with sharper time resolutions. An enhanced Kurtogram method used to diagnosis of rolling element bearing faults by Wang et al. [38]. This Kurtogram method is based on kurtosis of temporal signals that are filtered by the STFT. The Wigner-Ville distribution is also a popular time frequency analysis method. The Wigner–Ville distribution not use any window function therefore it is free from the interference between time localization and frequency resolution. The wavelet transform (WT) is the most popular method to diagnosis bearing faults [39]-[40]. The average of the wavelet amplitude frequencies on a selected band that is not affected by resonance of system was used by Rubini and Meneghetti [40]. Dalpiaz and Rivola [41] compared the effectiveness and reliability of wavelet transform method to other vibration analysis techniques. Mori et al. [42] have predicted the spalling on the ball bearing by applying discrete wavelet transform to vibration signals. Prabhakar et al. [43] have proved that the discrete wavelet transform can be used as an effective tool for detecting single and multiple faults in the ball bearings. Wang and Gao [44] proposed wavelet transform conjunction with Fourier transform to enhance feature extraction. Sun and Tang [45] have applied a singularity analysis on the continuous wavelet transform to diagnosis of bearing faults. This method spots the lines in the wavelet map that converge to singular points at fine scales. Jing and Qu [46] have developed a denoising method based on Morlet wavelets for feature extraction that is successfully applied it to detect inner race roller bearing fault. Some researchers [47]-[49] studied an advanced transform known as wavelet packet transform for vibration monitoring. Yunlong and Zhenxiang [50] presented a method of combination of kurtosis and wavelet analysis to diagnosis of rolling bearing fault. This method can detect quick and effectively bearing faults observed through experiment.

D. Other Techniques

Many other techniques have been used to diagnosis of rolling element bearing faults e.g. artificial neural networks (ANNs), fuzzy logic systems etc. Baillie and Mathew [51] proposed the application of ANNs to diagnosis of rolling element bearing faults. The main advantage of this time domain based model that can detect faults using short data length. Liu et

al. [52] have developed a fuzzy expert system for rolling element bearing fault diagnosis. Jack et al. [53] used radial basis function (RBF) networks for diagnosis of rolling element bearing faults but this network is fail to classify outer race and cage defects. Feedforward neural network (FFNN) structure is the mostly used neural network structure in the diagnosis of machine faults [54]. The performance of a multilayer feed-forward with the supervised training with that of an adaptive resonance theory (ART-2) based network with an unsupervised training algorithm has been compared by Subrahmanyam and Sujatha [55]. Samanta and Al-Balushi [56] have observed that a feed-forward ANN with two hidden layers is sufficient for the separation of bearings with and without faults. Antoniadis and Glossiotis [57] proposed an alternative framework for analyze rolling element bearing vibration signatures, based on cyclostationary analysis. Usually, the signal processing is done by the methods, which presume statistically stationary signal features. According to the non-stationary characteristics of vibration signatures of roller bearing fault, a fault diagnosis method based on empirical mode decomposition (EMD) energy entropy has been presented by Yang et al. [58]. Muruganatham et al. [59] presented a novel method to diagnose the bearing fault. This proposed method is based on the analysis of the bearing vibration signatures using singular spectrum analysis (SSA). They concluded that this method can detect the inner race bearing fault successfully with at faster rate and with very high accuracy. Kankar et al. [60] have investigated the fault diagnosis of ball bearings using machine learning methods. This research study is focused on diagnosis of ball bearing faults using artificial neural network (ANN) and support vector machine (SVM). The results demonstrate that the machine learning algorithms can be used for automated diagnosis of bearing faults. It was concluded that the accuracy of SVM is better than of ANN. Li [61] presented an intelligent fault diagnosis system of rolling element bearings combined with auto-regression (AR) model and RBF neural networks and concluded that it can detect fault pattern of rolling bearings accurately and the accuracy rate is more than 90%.

V. CONCLUSION

In this paper, an attempt to summarize the recent research and developments in the vibration analysis techniques for diagnosis of rolling element bearing faults has been made. This study found that the time domain techniques only can indicate the fault(s) present in the bearing but it can't identify the location. Frequency domain techniques have ability to identify the location of fault(s) in bearing. Vibration peaks generates in spectrum at the bearing characteristics frequencies, from that we can easily understand which bearing element is defected. Envelope analysis is very useful method to detect incipient failure of rolling element bearing. Time-frequency techniques can detect the bearing faults effectively due to its high resolution

capability. Many researchers have proved that the wavelet analysis is a better tool for fault diagnosis. A lot of research works have been done on the artificial neural network (ANN) and fuzzy logic based bearing fault diagnosis techniques. These techniques can detect bearing faults very fast with better accuracy.

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