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A Review of Vibration Analysis Techniques for Rotating Machines

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***Abstract*— The safety, reliability and efficiency of a rotating machine are of a major concern in an industry. Condition monitoring of a machine helps in retaining the efficiency and performance of a machine to its optimum level. The condition monitoring of a rotating machine is efficient, but often complex and labor intensive task for maintenance of the machine. Vibration analysis is a technique used for condition monitoring of the machine. Effective vibration signal extracting techniques have a critical role in efficiently diagnosing a rotating machine. Many vibration signal extracting techniques have been proposed during past some years. The paper presents review of some vibration feature extraction methods applied to different types of rotating machines.**

Keywords*— *Time domain, frequency domain, crest factor, fourier transform, wavelet.

I. Introduction

Rotating machines are widely used in today's industries. Some of these are very complex and critical for operation. The machine failure may result in costly downtime and loss of men and money. An effective diagnosis system is needed to predict the condition and reliable lead time of the machine. Therefore, an effective and efficient condition monitoring and fault diagnosis system is highly desirable in an industry. Vibration analysis is mostly used for fault detection in rotating machine.

II. VIBRATION ANALYSIS

It is natural for a machine to vibrate. Even in the best operating conditions machines will have some vibration because of small minor defects. Each machine has a level of vibration which may be regarded as normal. However, sometimes the machine vibration level increases or becomes excessive. Some mechanical trouble is usually the reason. The reasons behind the excessive vibration include- unbalance, misalignment, worn gears or bearings, looseness etc. The vibration level of the machine is measured with the help of sensors. These are proximity sensor, velocity transducer and accelerometer. Accelerometers are mostly used for vibration analysis.

Fault diagnosis in the rotating machine is conducted in the following steps- data acquisition, feature extraction and fault detection. Effective features extraction very critical foe the efficient fault diagnosis system.

Vibration signals collected by signals are often contaminated by noise signals. These contaminated signals can be unfit for fault diagnosis. Without the assistance of some certain techniques the vibration features or signatures can go undetected. Feature extraction techniques can locate certain components in signals to help detection of machine faults [1]. Various vibration analysis techniques have been applied to the fault diagnosis of the rotating machines. In past some decades, some study has been done in reviewing vibration techniques from a different point of view. In 1980's Mathew and Alfredso presented a review of vibration monitoring techniques in time and frequency domain for rolling element bearings [2]. McFadden, Smith [3] and Kim [4] included classical non-parametric spectral analysis, principal component analysis, joint time frequency analysis and the discrete wavelet transform. Lebold and McClintc [5] reviewed statistical method for extracting features for gearbox fault diagnosis. Tendon and Chaudhary [6] reviewed vibration and acoustic measurement techniques for rolling element bearing fault analysis. Tashin Doguer and Jens Strackeljan [7] reviewed time domain feature extraction for diagnosing small roller bearing defects.

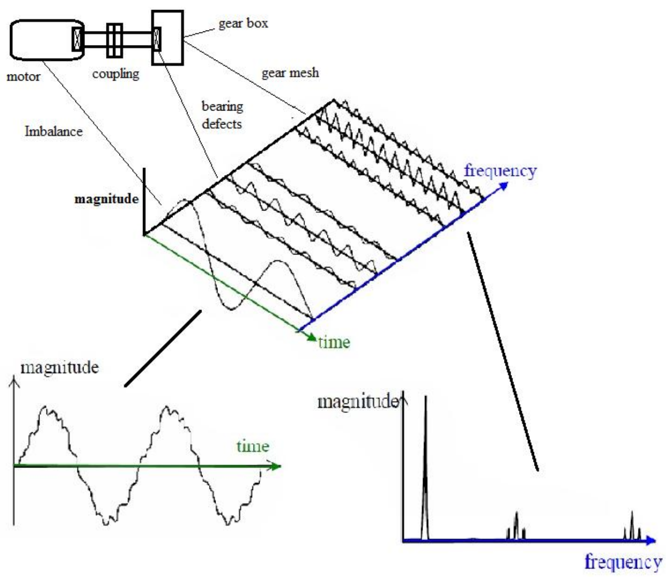

Fig- Overview of Vibration Analysis

In this paper a review of vibration analysis techniques for a variety of rotating machines is presented. These techniques are grouped in three categories, time domain, frequency domain and time-frequency domain as shown in figure. In each category diverse range of techniques are presented, some of which are based on common principles.

A. Time domain

Vibration signals are obtained as a series of values representing proximity, velocity or acceleration in the time domain. This section presents recent study on vibration techniques in the time domain. These techniques are categorized in the following groups as shown in the table 1-

Time domain			
Raw signals		Filter based methods	Stochastistic and advanced methods
Statistical parameters	Time Synchronous Averaged Signal (TSA) based methods		
- Root mean square (RMS) - Mean - Variance - Skewness - Kurtosis - Crest factor	- Time Synchronous Averaged (TSA) signal - Resudual signal (RES) - Difference signal	- Demodulation - Prony model - Adative noise cancelling	- Chaos - Blind deconvolution - Thresholding - Autoregressive model based methods

Table 1- Time Domain Vibration Analysis Techniques

Statistical parameters- these include Root Mean Square (RMS), Mean, Variance, Skewness, Kurtosis and Crest factor.

Root mean square value and crest factor has been applied in diagnosing bearings and gears [6]. The RMS value of a vibration signal is a time domain feature. It presents the power content in the vibration. RMS value is very helpful in detecting imbalance in rotating machinery. In the time domain RMS value is the most basic method used to detect the faults in rotating machine, but this is not capable of detecting faults when the problem is in early stage.

Crest factor is another measure in the time domain vibration analysis. Crest factor is defined as the ratio of the peak value of the input signal to the RMS value. In time series signal peaks will result in an increase of the crest factor value. In rotating machines tooth breakage or fault in outer race of bearing leads to generation of impulse vibration signals. Here the crest factor will be high so it helps in detecting faults in gear tooth or bearing.

Statistical analysis is useful in detecting faults in industrial machinery. Tandon [6] review the time domain vibration analysis for detecting faults in bearing. He showed that probability function is correlated with bearing defects. The probability density of acceleration of a bearing in good condition has a Gausian distribution, whereas for a defected bearing the probability density distribution is non-Gausian and with dominant tail. This is because of increase in no. of high acceleration signals. Mathew and Alfredson also showed non-Gausian distribution for defected bearing. Andrade[8] compared the Cumulative Density Function (CDF) of a vibration signal with the CDF of a reference distribution to detect gear tooth fatigue crack.

Statistical moments are also helpful in vibration analysis. Mean, variance and skewness are first, second and third moment of probability distribution respectively. Kurtosis is the fourth moment of probability distribution. It measures the flatness of a distribution to a normal distribution.

The root mean square, peak value, kurtosis and crest factor have been combined with high frequency resonance techniques to detect damage in roller bearings [10].

Time Synchronous averaging (TSA) method- It includes Time Synchronous Average (TSA) signal, residual signal (RES) and difference signal (DIFS).

Time synchronous averaging is a signal processing technique which extracts periodic waveform from noisy data. The TSA signals are obtained by time synchronous averaging of primary vibration signals and reducing the redundant noise. TSA allows the vibration of the gear under analysis to be separate from other rolling components. It separates the noise sources from the vibration signals which are under watch. The signals after TSA can provide the information related to the faults. Synchronous averaged signals have been utilized for fault diagnosis rolling element bearings and gears [10-11]. Eric Bechhoefer [12] reviewed the TSA technique and showed that it has similar performance in time and frequency domain.

Residual signal (RES) was used by Lebold [5] for gear diagnosis. He used RES consisted of the time synchronous averaged signal with the primary meshing and shaft components along with their harmonics removed. Difference signals (DIF) are calculated by removing the regular meshing components from the time synchronous averaging signals. The DIF was used for gear fault diagnosis effectively [13].

Filter based methods- these methods include demodulation, prony method and adaptive noise cancelling (ANC).

Filters are used in feature extracting techniques for removing contaminated noise and isolated signals from raw signals. These methods are generally called filter based methods. Demodulation, prony model and adaptive noise cancelling are filter based methods.

Demodulation, which includes phase and amplitude demodulation, is a widely used signal processing technique. The amplitude demodulation is also called envelop, or resonance demodulation, or high frequency demodulation technique. Amplitude demodulation is a process which separates low level low frequency signal from background noise [14]. This enables the signal to be easily measured. Amplitude demodulation has been applied successfully in the diagnosis of gears [15] and bearings [16] faults. The phase demodulation emphasized the band associated with the structural resonance excited by the fault induced impacts [14].

Demodulation uses a conventional Infinite Impulse Response (IIR) filters such as Butterworth, Chebyshev, Bessel and Elleptic in pass band or stop band. A Prony model based technique was applied by Chen Z [17] to bearing fault diagnosis. Prony's model is an algorithm for finding an IIR filter with a prescribed time domain impulse response. Li Z and Fu Y [18] used adaptive filter for diagnosing bearing faults. Adaptive noise cancelling technique has been applied successfully for detecting faults in roller bearing [19]. Noureddine [20] shows that Prony based model is very effective in detecting fault in gear box.

Stochastic methods- these include chaos, blind deconvolution, thresholding, and autoregressive model based methods.

Stochastic parameters have been used for vibration analysis in time domain. Chaos and the correlation dimension have been used to identify many induced faults of different severity in a rolling element bearing [21]. The correlation dimension is helpful in classifying different faults intelligently [22]. Nirbito [23] proposed and studied the suitability of blind deconvolution for the enhancement of bearing signals which were corrupted by noise signals. Threshold denoising (which include soft thresholding and hard thresholding) have been used to denoise vibration signals. The thresholding denoising methods can be used by combining it with envelop or some other methods together for rotating machine fault diagnosis. Soft thresholding method and hard thresholding methods are also being used for rotating machine fault diagnosis [25]. The autoregressive model base has been applied by Wang, W [26] in fault diagnosis.

B. Frequency domain and Time-Frequency domain

At present frequency domain features and time-frequency domain features are widely used for vibration analysis of rotating machine. Generally frequency domain features are more capable than time domain features in indicating the faults in rotating machine. This is because the resonance frequency component or the fault frequency component can be detected more easily in frequency domain features as compare to time domain features.

Appropriate vibration techniques need to be selected as per the need to obtain optimal output from vibration analysis. Some developed frequency domain techniques and time-frequency domain techniques are given in the table 2.

This section includes the Fast Fourier Transformation (FFT) and various time frequency representations and time frequency scale analysis techniques. The table shows Frequency and time-frequency analysis methods which are being currently used for analysis of vibration signals of rotating machines.

Frequency domain analysis or spectral analysis of vibration signals is most widely utilized technique for bearing fault detection. The Fast Fourier Transform (FFT) is mostly used diagnosis technique to identify the frequency features of vibration signals. These signals may be raw signals or processed signals.

The power spectrum whose amplitude is the square of the amplitude of the vibration spectrum is more effective method to diagnose fault in rotating machine. The higher order spectrum is also called bispectrum and it can be applied for rotor bearing fault diagnosis [29].

The bicoherence is a third order vibration spectrum it is used to measure the phase coherence among three spectral components due to non linear wave coupling. It has been for bearing faults diagnosis [30].

First order	Second order	Third order	Fourth order
Spectrum (FFT)	Power spectrum Power cepstrum (Logarithm of of power spectrum)	Bicoherence spectrum	
Correlation of spectrum, signal averaging	Cyclostationarity	Bilinearity	
Short time Fourier transform (STFT)	Spectrogram Wigner distribution	Wigner bi spectra	Wigner tri spectra
Continuous wavelet transform(CWT)	Scalogram		
Discrete wavelet transform(DWT)			
Discrete wavelet packet analysis (DWPA)			
Time-averaged wavelet spectrum (TAWS)			
Time-frequency scale domain (TFS)			

Table 2- Frequency Domain and Time-Frequency Domain Techniques

Power cepstrum is the logarithm of the power spectrum. Power cepstrum has been successfully used for rotating machinery fault diagnosis [6].

Cycloststionary is the second order of a frequency domain synchronised averaging method. The second order cyclostationary is an effective tool used for detecting early faults in gear system. It has been used for early diagnosis in gear system [31]. Bouillant L and Sidahmed [32] compared the cyclostationary and bilinearity and applied cyclostationary for early diagnosis of helicopter gearbox.

During the past years time-frequency domain vibration analysis techniques have been researched and applied for machine diagnosis. The main feature of these time-frequency techniques is that these are capable of representing vibration signals in both time and frequency domain. This characteristic helps in analyzing vibration signals which are non stationary. Initially time-frequency analysis techniques, windowed Fourier transform [33] and Short Time Fourier Transform (STFT) were used for machinery condition monitoring.

The Winger distribution [35] and spectrogram [36] are the well known quadric time frequency representations which are used for diagnosing gear faults. The nature of such signals sauses significant interfering crosss-terms which do not permit a straight forward interception of energy distribution. The directional Choi-Williams distribution (dCWD) was proposed for rotating machinery fault diagnosis [37]. Directional Winger distribution (DWD) has been applied in analysing the order of rotating machine [38].

The third and fourth order Winger moment spectra also called Winger bi-spectra and Winger tri-spectra were also used for rotating machine vibration signals [39]. The fourth order Winger moment spectra has been applied for diagnosis of valves system faults in an engine [40].

The continuous wavelet transform (CWT) is developed base on Short Time Fourier Transform (STFT) with better time frequency resolution. It has been applied in fault diagnosis of of rotating machine. The scalogram, second order frequency modulus of CWT was applied for gear fault analysis [26].

The Discrete wavelet transform (DWT) was used to diagnose spalling in ball bearings [42]. Discrete wavelet packet analysis (DWPA) [43] and discrete wavelet analysis [44] have also been used in fault diagnosis. A time frequency scale domain (TFS) is also useful in diagnosis of rotating machine faults.

III. CONCLUSION

Vibration feature extraction techniques have a critical role in fault diagnosis of rotating machine. The feature extracting techniques are improving all the time. Now with increasing use of computer science the vibration analysis is becoming more efficient and effective.

Time domain techniques include raw signals, filter based signals, stochastic and model based methods. The statistical values such as RMS, mean, kurtosis and crest factor are compared with threshold value for fault detection in rotating machines. Time domain vibration signals have some limitations for detecting early fault generation. So the research has been conducted for increasing sensitivity of statistical parameters. Filter based methods such as modulation are being used effectively which separate fault signals from unwanted signals such as noise.

Frequency domain features are generally more effective in detecting faults as compared to time domain features. Time frequency domain features are useful in diagnosis of non stationary vibration signals. The research is being conducted to increase the order of transformation parameters. Time frequency techniques are also being researched for analysing vibration signals for specific applications. For example the dyadic discrete wavelet transform is used for low frequency bands rather than high frequency bands. Discrete wavelet packet analysis is applicable for both low frequency and high frequency bands, so making it more powerful for rotating machine fault analysis.

Researches are being conducted for automating diagnosis procedures. Tools such as expert systems, neural network, and fuzzy network are being used with above discussed techniques for increasing effectiveness of fault diagnosis.

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