CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

Among the other mechanical components, researchers pay great attention to the rolling element bearings due to their unquestionable industrial importance. In addition, more faults arising in rotating machines are often linked to bearing faults. The result of many studies show that bearing problems account for over 40% of all machine failures (Schoen et al 1995). Major causes of premature bearing failure are listed in Table 2.1.

<table>
<thead>
<tr>
<th>Causes</th>
<th>Failure rate in %</th>
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<tbody>
<tr>
<td>Dirt</td>
<td>45.4</td>
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<td>Misassembly</td>
<td>12.8</td>
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<td>Misalignment</td>
<td>12.6</td>
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<td>Insufficient Lubrication</td>
<td>11.4</td>
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<td>Overloading</td>
<td>8.1</td>
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<td>Corrosion</td>
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<td>Improper Journal Finish</td>
<td>3.2</td>
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Rolling element bearings generally consist of two rings, an inner and an outer, between which a set of balls or rollers rotate in raceways.
Eschmann et al (1958) stated that when bearings operate under normal conditions of well balanced load and good alignment, fatigue failure begins with small fissures. These fissures are located between the surface of the raceway and the rolling elements, which then gradually propagate to the surface, generating detectable vibrations and increasing noise levels. Riddle (1955) observed the fatigue phenomena, known as flaking or spalling and suggested that continued stress causes fragments of the material to break or loose, and produce a localized fatigue. Once fatigue gets started, the affected area expands rapidly contaminating the lubricant and causing localized overloading over the entire circumference of the raceway, noticed by Eschmann et al (1958). Eventually, the failure results in rough running of the bearing. This is the initiation of failure in rolling element bearings which reduce the life of the bearing.

According to Riddle (1995) external sources include contamination and corrosion. Improper lubrication also affects the life of the bearing. The dirt and foreign matter that is commonly present in most of the industrial environment and the abrasive nature of these miniature particles, whose hardness can vary from soft to hard like diamond, cause pitting and sanding action responsible for measurable wear of the balls and raceways.

Riddle (1955) stated that improperly installed bearings are often caused by forcing the bearing onto the shaft or in the housing. This produces physical damage in the form of brinelling or false brinelling of the raceways which leads to an early failure. Brinelling is the formation of indentations in the raceways as a result of deformation caused by static overloading.

Misalignment of the bearing is the result of one of the improperly installed shafts and bearing, which occurs in four ways depicted in Figure 2.1. It is also a common result of defective bearing installation. The most common of these is caused by tilted races.
The presence of water, acids, deteriorated lubrication and even perspiration from careless handling during installations produce bearing corrosion. Eschmann et al (1958) and Riddle (1955) observed the effects of improper lubrication that includes both under and over lubrication. In either case, the rolling elements are not allowed to rotate on the designed oil film causing increased levels of heating. Consequently, the excessive heating causes the grease to break down, which not only reduces its ability to lubricate the bearing elements but also accelerates the failure process.

2.2 STUDIES RELATED TO TIME DOMAIN ANALYSIS

Time domain refers to a display or an analysis of the vibration data as a function of time. Tandon and Nakra (1993) reported visual inspection of the time history of the vibration signals, time wave form indices, probability density function, and probability density moments that are easily analyzed using the time domain analysis. A time wave form index is a single number calculated, based on the raw vibration signal and used for trending and comparisons. The indices include peak value, mean value, rms value, and peak-to-peak amplitude. This method has been applied with only limited success for the detection of the defects.
Probability density function is the measure of the probability of finding the instantaneous amplitude value from a vibration signal within a certain amplitude range. The shape of probability density function will be similar to a Gaussian or normal probability distribution for a bearing in good condition. Mathew and Alfredson (1984) reported obtaining a new Gaussian distribution for some damaged bearing also. Probability density moments, which are based on the probability density function, are more informative. Probability density moments are of two types namely odd and even moments. Odd moments that are the first and third moments, indicate the mean and skewness. They reflect the probability density function peak position, relative to the mean. An even moment, like second and fourth, represents the standard deviation and kurtosis, which are proportional to the spread of the distribution. The most useful is the kurtosis, which is sensitive to the impulsiveness in the vibration signal. Therefore, it is sensitive to the type of the vibration signal, generated in the early stage of a rolling element bearing fault. Dyer and Stewart (1978) first proposed the use of kurtosis for bearing fault detection. Several studies have shown the effectiveness of kurtosis in the detection of bearing defect. It is a mathematical representation given in equation (2.1) of deviation of amplitude distribution from the Gaussian. It indicates the spread of distribution:

\[
\text{Kurt} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{x(i) - \mu}{\sigma} \right)^4
\]  

(2.1)

where \( x = \) instantaneous amplitude, \( \mu = \) mean, and \( \sigma = \) standard deviation.

Kurtosis can be assimilated with a shape factor, the value of which does not depend on the signal amplitude:

- Sine signal : Kurt = 1.5
- Square signal : Kurt = 1
Gaussian signal : Kurt = 3
Pulse Signal : Kurt > 3

Figure 2.2 Calculation of kurtosis in the sliding window of a pulse signal

Figure 2.2 shows evidencing the great sensitivity to shocks exhibited by kurtosis. It is particularly suited to monitoring of bearings of low speed rotating shafts, where frequency-based techniques are limited. The kurtosis value is close to 3 for good condition bearing. During the early stages of a fault, the kurtosis increases and decreases in value as the fault gets worse. Martin and Honarvar (1995) provided a low cost tool for both maintenance and quality control applications. For this purpose, the damage mapping approach is used to characterize surface formation in addition to surface damage. Chinmay and Mohanty (2004) discussed the possibility of application of Kolmogorov and Smirnov (KS) test in diagnosing rolling element bearing defect identification. Local defect can be detected in the time domain by displaying the vibration signal and by observing the presence of the periodic peak due to the impact of the defect in the studies of Alfredson and Mathew (1985), Igarashi and Hamada (1982 ) and Igarashi and Kato (1985). A new method of diagnosis by Shao and Nezu (1996) delineated the
use of laser displacement sensor for monitoring the bearing vibration. The advantage of using the laser displacement sensor is its lightweight, small size, and high precision. The method used provides a new means of failure diagnosis of machinery.

The principal advantage of the time domain is that no data are lost before inspection. However, the major disadvantage is the requirement of too much data for easy and clear fault diagnosis. From the above said methods, it is clearly evident that only very little amount of data is used for identifying the defect. This method is not possible to detect the defect of the bearing and severity of the defect in the bearing elements. Hence a sophisticated high resolution vibration analyzer is needed for data collection.

2.3 STUDIES RELATED TO FREQUENCY DOMAIN ANALYSIS

The frequency domain refers to the display of data on vibration based on the frequency. Fast Fourier Transform (FFT) is typically used to convert the time domain vibration signal into the frequency domain. The principle advantage is that the repetitive nature of the vibration signals is clearly displaced as peaks in the frequency spectrum at the frequency where the repetition takes place. The interaction of the defect in the rolling element bearings produces pulses of very short duration. These pulses excite the natural frequency of the bearing elements, resulting in the increase in the vibration energy at these high frequencies. Each bearing element has a rotational frequency. With a defect on a particular bearing element, an increase in the vibration energy at this elements characteristic rotational frequency may occur. This defect frequency can be calculated from the geometry of the bearing and elements rotational speed by Alfredson and Mathew (1985). Figure 2.3 shows the vibration spectrum of a rolling element bearing with an inner defect.
Igarashi and Hamada (1982) investigated the vibration and sound of the rolling bearing with one dent and reported the success of the method. A model proposed by McFadden and Smith (1984, 1985) described the vibration produced by a single point defect on the inner race. Su and Lin (1992) investigated the frequency characteristics of vibration for bearing with defect under diverse loadings. Taylor (1980), Tandon and Nakra (1993) and Johnson (2000) reported the success in bearing defect detection by identifying the rotational frequency.

The analytical model proposed by Tandon and Choudhury (1997) predicted a discrete spectrum having peaks at the frequencies and its harmonics. The studies conducted by Yiakopoulos et al (2005) showed that the slip motion of the rolling elements of bearings introduces a nonlinear effect. This affects the quality of the information about the bearing health presented in the spectrum. Bearing defects amplify the magnitude of the characteristic defect frequencies in the presence of a high background noise. Adaptive noise cancelling (ANC), as it is widely known, is a method that
improves the signal to noise ratio. ANC is a method of estimating signals corrupted by additive noise. It has been shown by Chaturvedi and Thomas (1981) that the statistical and spectral analysis techniques can be made more effective in their diagnostic roles after the application of ANC. Figures 2.4 (a) and (b) shows the result of de-noising.

![Image of Figures 2.4 (a) Signal from defective bearing (b) Result of de-noising signal](image)

**Figure 2.4 (a) Signal from defective bearing (b) Result of de-noising signal**

McFadden and Smith (1984), Prasad et al (1985) used the new method called high frequency resonance technique (HFRT) or envelope technique. They proved that these frequencies could be isolated and demodulated to give an indication of bearing condition. In fact, the envelope detection process is the heart of the HFRT diagnostic system. Martin and Thorpe (1992) presented a normalizing technique, which was the extension of the envelope technique. It gave much greater sensitivity to the detection of the defect frequency. The paper by Campbell and Tawakoni (1996) discussed the ability of various
techniques to detect and trend the damage in needle bearings. Hansen and Gao (2000) presented an analysis of the vibration of a deep groove ball bearing with an integrated force sensor. The force sensor is accommodated within a slot in the bearings outer race. The findings validated the approach of integrated sensing for online condition monitoring. Mohamed (2009) presented the effect of partial rotor-to-stator rubbing is investigated both experimentally and analytically. It is found that due to rubbing the measured vibration signal is distorted showing a flattened portion in the waveform. It is also indicated that light rubbing induced vibrations are characterized by harmonics at frequencies equal to 1X, 2X and 3X revolutions, whereas, severe rubbing is identified experimentally by a spectrum containing subharmonics at 1/3 and 2/3 of the rotational frequency.

2.4 STUDIES RELATED TO UNBALANCE AND MISALIGNMENT

For many decades, it had been common to use solid couplings in turbo machinery. However, these couplings have a decisive influence on rotor dynamics. Sekhar and Prabhu (1995) presented the effects of coupling misalignment on turbo machinery vibrations. It was shown that the location of the coupling with respect to the bending modes shape has a strong influence on the level of vibration. A theoretical model of a complete motor flexible coupling rotor was presented by Xu and Marangoni (1994). They assumed that the flexible coupling behaves exactly as a universal joint to take the misalignment and unbalance effects into account. Figure 2.5 shows the frequency spectra of misaligned system of different coupling. Prabhu (1997) showed that an increase in misalignment had caused a change in the second harmonic of the vibration response. Simon (1992) predicted the behavior of a large turbo-machinery when subjected to unbalance and misalignment. Figure
2.6 displays the frequency spectra of the misalignment and unbalanced condition. Dewell and Mithchell (1984) developed the expected vibration frequencies for a misaligned metallic disk-flexible coupling. The predicted dominant frequencies were 2X and 4X running speed components due to parallel misalignment.

Figure 2.5  Frequency spectra of misalignment (a) Helical coupling and (b) Self designed coupling (Simon 1992)

Figure 2.6  Frequency spectra of misaligned and unbalance helical coupling 35.71 Hz and 41.05 g-cm and (b) 35.29 Hz and 16.56 g-cm  (Simon 1992)
Wattner (2002) dealt with the design functions and case histories of gear couplings. He discussed the various types of misalignments, which may be encountered by the gear type of coupling. Palazzolo et al (2008) discussed forces and moments, induced by gear coupling misalignment. They reasoned that gear couplings can produce large static forces that can affect the vibration of turbo machinery. Bloch (2002) showed how a change from conventional gear-type couplings to more recent diaphragm coupling design could lower shaft stresses sufficiently to avoid shaft replacement during power up rates of centrifugal compressors. Gibbson (1997) derived the reaction forces generated by the different types of couplings. Mancuso (1995) discussed the applications of flexible-type couplings for turbo machinery. Rosenberg (1958) presented the critical speed behavior of rotating shafts driven by universal coupling. Due to rotation, vibration effects caused by a fault may occur periodically, making the frequency domain a source of many useful features. FFT analysis of harmonics and sub harmonics of main frequencies, such as bearing shaft speed or gear meshing frequency, is a typical source of features for both identifying an existing fault mode and diagnosing said fault. Typically, the first two harmonics, 1X and 2X, contain the most relevant information about the system behavior, in multiple frequency-based domains such as FFT, full-spectrum, auto-spectrum, or wavelet by Patel and Darpe (2009)

2.5 STUDIES RELATED TO BEARING WEAR BY SOLID CONTAMINANTS PRESENT IN LUBRICANTS

Surface initiated damage due to lubricant contamination has become one of the main causes of bearing failure. Kegg (1984) stated that up to 80% of the downtime is spent locating the source of the fault. Bertele (1990) and Neale (1985) suggested that practically an application of condition monitoring techniques may help in early fault detection. In their study on
hydrodynamic lubrication regime occurring in rolling bearing, high contact pressures are developed in the surfaces to deform elastically, giving room for small elliptical contact areas. The development of sites of elastic deformation is susceptible to the existence of material defects near the subsurface region, as well as to the presence of hard particles in the contact interface.

Su et al (1993) dealt with the effect of surface irregularities on roller bearing vibrations. A mathematical model is proposed to show the frequency characteristics of roller bearing vibrations. The frequency characteristics of normal roller bearing vibrations, induced by manufacturing errors of components, have been investigated. Ohta and Kobayashi (1996) dealt with the vibration of hybrid ceramic ball bearings. In hybrid ceramic ball bearings, ceramic balls and steel rings have been widely used in high speed spindles for machine tools, replacing conventional steel ball bearings. Radivoje Mitrović and Tatjana Lazović (2002) investigated upon the frictional sliding which follows rolling of balls along the rings raceways. This one causes rolling bearing to wear.

Zeki Kiral and Hira Karagulle (2003) were concerned with simulation and analysis of vibration signals generated by rolling element bearings. In their study, a finite element method to dynamic loading models for healthy and defected rolling element bearing structures has been developed. It also studied the vibration response of the bearing structure. Tomimoto (2003) taking a keen interest in plain bearings, opined that an increase in contaminant concentration could decrease the thickness of the oil film. Larger size particles have greater tendency to cause early fatigue spalling in the contact zone. Besides spalling, contaminant particles can lead to other damage mechanisms, such as scuffing. They originate from the lubricant starvation at the inlet of the contact zone. Izzet Onel et al (2005) dealt with the detection of outer raceway defects in bearings. Experiments are
presented using Motor Current Signature Analysis (MCSA) that clarifies some of the factors that may affect the indication of outer race defects of ball bearings. Fast Fourier Transform (FFT) is used to the stator current to observe the defects.

2.6 STUDIES RELATED TO VIBRATION DUE TO DISTRIBUTED BEARING DEFECTS

The main class of bearing problems can be characterized as “distributed” defects, which involve the entire structure of the bearing. It includes surface roughness, waviness, misaligned races, and off-size rolling elements. These defects often give rise to excessive contact forces, which in turn result in premature surface fatigue and ultimate failure. Tallion and Gustafsson (1965) experimentally explored spectral properties of bearings outer ring vibration as a function of speed, load, waviness, and other geometrical parameters. A mathematical model for ball bearing vibrations was proposed by Meyer et al (1980). The model allows a family of distributed defects to be simulated and the spectral components resulting from these defects to be predicted. Sunnersjo (1985) studied the vibration characteristics of the bearings having inner race waviness and varying ball diameter and found that significant peaks occur at the cage speed for a non uniform ball diameter.

Yhland (1992) proposed a linear model for the vibrations of the shaft bearing system caused by ball bearing geometric imperfections. These imperfections covered are radial and axial waviness of outer and inner rings, ball waviness, and ball diameter oversize. Choudhury and Tandon (1998) extended the model proposed by Meyer to predict the vibration response of radially loaded bearings with distributed defects. Aktürk (1999) simulated the effect of bearings surface waviness on the vibration by a computer program.
The results are obtained in both time domain and frequency domains. Loparo et al (2000) presented a model-based technique for the detection of faults. Jang and Jeong (2003) proposed an analytical method to investigate the stability of a rotating system due to ball bearing waviness. Amaranth et al (2004) dealt with the suitability of vibration monitoring and analysis techniques to detect defects in anti-friction bearing. Ilonen (2005) introduced a generic condition diagnosis tool. The tool successfully detected bearing damage in induction motors using measurements of the stator current or vibration. It is based on discriminative energy functions that reveal discriminative frequency-domain regions where failures can be identified. Purohit (2006) discussed the radial and axial vibrations of rigid shaft supported by ball bearings.

2.7 STUDY RELATED TO ACOUSTIC EMISSION TECHNIQUE

Acoustic Emission (AE) was originally developed for non-destructive testing of static structures. However, over the years, its application has been extended to health monitoring of rotating machines and bearings. One of the earliest documented applications of AE technology for monitoring the rotating machinery was in the late 1960s in an article by Mba and Rao (2006). They presented the review of application of AE to condition monitoring and diagnose rotating machinery. Rogers (1979) utilized the AE technique for monitoring slow rotating anti-friction slew bearings on cranes. AE is the phenomena of transient elastic wave generation due to a rapid release of strain energy. It is caused by a structural alteration in a solid material under mechanical or thermal stresses. AE can be related to grain size, dislocation density, and the distribution of the second phase particles in crystalline materials. Kannatey-Asibu and Dornfeld (1982) observed them during the deformation of the material. Braun (1980) discussed monitoring of
roller bearings by applying the signature analysis method to sonic signals, generated during the operation. In this study, he reviewed the mode of bearing failure, mechanisms of signal generation, and the signal modification introduced by structural paths and instrumentation. In addition, he mentioned a few specialized methods such as generalized periodic function, variance analysis, and amplitude domain techniques.

Yoshioka and Fujiwara (1981) showed that bearing defects are identified before they appeared in the vibration acceleration range by AE parameters. Lyon and Ordubadi (1982) discussed the cepstral analysis to signal recovery in the acoustic system called non-linear filtering technique. After that, AE transducers are designed to detect the very high frequency (450 kHz) stress waves that are generated when cracks extend under load. The most commonly measured AE parameters are peak amplitude, counts, and events of the signal. The advantage of the AE technique over the vibration technique is that it can detect the growth of the subsurface cracks, whereas the latter can detect them only when they appear on the surface. Tandon and Nakra (1990) demonstrated the usefulness of some acoustic parameters, such as peak amplitude and count for the detection of the defect in bearings.

Al-Ghamd and Mba (2005) carried out an investigation on the suitability of AE for identifying bearing defect and it is more sensitive than the vibration method. Second, AE response and the defect size can be related, which was not the case for the vibration signature. Tandon et al (2006) made a comparative study of condition monitoring techniques for the detection of defect in induction motor ball bearings. In this study AE monitoring proved to be the best method, followed by the shock pulse method. Noise is produced by vibration, eccentricity, surface irregularities and impact. The acoustic emission technique has also been employed by Miettinen et al (2000) to monitor the lubricant condition in rolling element bearing. Successful
applications of AE to bearing diagnosis for extremely slow rotational speeds have been reported by Mba et al (1999) and Jamaludin et al (2001). The propagation of the acoustic emission is affected by material microstructure, inhomogeneities, geometrical arrangement of free surfaces, loading conditions and the number of component interfaces.

2.8 STUDIES RELATED TO WAVELET TECHNIQUES

To overcome the limitations of FFT in analysis, of the non-stationary signals, the short-time Fourier transform (STFT) and wavelet analysis were introduced. Tse et al (2001) used wavelet transform as a mathematical tool with a powerful structure and enormous freedom to decompose a given signal. It consisted of several scales at different levels of resolution. Wavelet analysis provides a good resolution at the low frequency range and a fine resolution at high frequency range. Such a multi-resolution capability is essential for vibration based machine fault diagnosis Jing et al (2004). Yang and Ren (2004) proposed a wavelet-based envelope analysis method for impulse detection.

Rothberg and Halliwell (1994) designed a laser vibrometer for the non-linear vibration measurement directly for a rotating component. A force model, simulating the force variation and impact formation, when the rolling elements roll over a local defect, is proposed by Kiral and Karagulle (2003). The maintenance industry has adopted HFRT as one of the main tools in the condition monitoring program for early bearing fault-detection stated by Li et al (2004) and DiMaggio and Sako (2001). Generally, the traditional HFRT is based on the Hilbert transforms (HT), or the Fast Fourier transforms (FFT). However, there are two limitations as follows:
(i) The HFRT demands on the knowledge of the resonance frequency range where the defect generated impulses are more pronounced with respect to normal system vibrations;

(ii) Owing to the overlap of each transient component, a traditional HFRT may not be able to identify each defect, when there are multiple defects developed at the same time. HFRT is algorithm based on Maximal Overlap Discrete Wavelet Packet Transformation (MODWPT). In this algorithm, Peng and Chu (2004) proposed the “wavelet coefficients usable for analysis of variance” and “Shift invariant transformation”.

Khalid et al (2007) suggested an alternative approach based on the Laplace-wavelet enveloped power spectrum. The Laplace-Wavelet shape parameters are optimized based on Kurtosis maximization criteria. Khalid et al (2009) applied a new technique for rolling element bearing fault diagnosis based on the autocorrelation of wavelet denoised vibration signal. The wavelet base function has been derived from the bearing impulse response. To enhance the fault detection process, the wavelet shape parameters (damping factor and centre frequency) are optimized based on kurtosis maximization criteria. In order to effectively diagnose faults for rotating machinery in the variable rotating speed, a novel diagnosis method is proposed. It is based on time-frequency analysis techniques, the automatic feature extraction method, and fuzzy inference. The diagnosis sensitivities of three time-frequency analysis methods, namely the short-time Fourier transform (STFT), wavelet analysis (WA), and the pseudo-Wigner-Ville distribution (PWVD), are investigated for condition diagnosis of rotating machinery by Huaqing Wang and Peng Chen (2010).
2.9 STUDIES RELATED TO AUTOMATIC DIAGNOSIS SYSTEM

The AE technique needs a human interpretation to analyze the result. When the amount of data collected is more or the plant size is large, then the analysis becomes difficult. In this situation, an automated system providing concise and reliable assessment of the machine condition is very essential. Qiao et al (2004) explored pattern recognition technique for an automatic machinery fault diagnosis to feature extraction, mapping for feature fusion, nonlinear learning, classification, and decision making. Herein emerges Artificial Neural Network (ANN) as a popular tool for signal processing and pattern classification task. Not only that, it is suitable for condition monitoring purposes as well. Alguindigue et al (1993) believed that the capacity of ANN to mimic and automate human expertise is what makes it ideally suitable for handling non-linear systems. Other researchers like Tse and Atherton (1999), Li et al (2000), Kalkat el al (2003) also averred that ANN could be used for false detection.

The presence of a bearing defect makes it impossible to determine the degree of imbalance based on a single vibration feature. In such a case, it is necessary to employ diagnostic techniques that are suited for parallel processing of multiple features. NNs are the best known techniques to approach such a problem. Hoffman and Vander Merwe (2002) demonstrated that a neural classifier, using the X and Y components of both the peaks at rotational frequency and at ball-pass outer race frequency as input features, can reliably diagnose the presence of bearing defect. It can also indicate the degree of imbalance. Hidden Markov Modeling (HMM) is known as a state-of-the-art technique for speech recognition. Purushotham et al (2005) narrated that this method is very accurate in the detection of both single and multiple bearing faults under different operating conditions. HMMs have also been
successfully applied to monitor machine tool wear by Ocak and Loparo (2005). Khalid et al (2008) used time domain vibration signals of rolling bearings with different fault condition are pre-processed using Impulse and Laplace wavelet transforms. The extracted features for the predominant wavelet transform coefficients in time and frequency domain are applied as input vectors to artificial neural networks for rolling bearing fault classification.

The diagnosis system for rolling bearing faults based on virtual instrument is a new attempt at connecting virtual instrument technology and rolling bearing fault diagnosis technology. It not only simplifies the process of system design, but also increases the flexibility and extension ability greatly. Proposing this diagnosis system, Pan et al (2006) succeeded in combining modern virtual instrument technology and Hilbert’s transform envelope analysis method. This system is based on an intelligent control-oriented Virtual Measurement Instrument Developing System (VMIDS) and developed by the Test Center of Chongqing University. VMIDS is a virtual plant that can develop an intelligent virtual control-oriented instrument, with functions of design, assembly, modification, consultation, and storage. Jiang Tao Huang et al (2010) proposed a novel intelligent method for fault diagnosis based on empirical mode decomposition, fractal feature parameter extracting and orthogonal quadratic discriminant function classifier. It consists of three steps. Firstly, with investigating the feature of impact fault in vibration signals, the raw vibration signals are decomposed into intrinsic mode functions by empirical mode decomposition. Secondly, using the method of time sequences fractal dimension calculating, fractal feature parameters are extracted from intrinsic mode functions. Then, each raw signal sample has a feature set. Finally, training set and testing set are inputted into the orthogonal quadratic discriminant function model in the classification phase to identify different abnormal cases.
2.10 CONCLUSION FROM LITERATURE REVIEW

The literature review revealed the following:

- Mostly for the bearing fault diagnosis, time domain and envelop frequency signals are used. However, it is reported that for easy and clear fault diagnosis, larger data are required especially when time domain analysis is used.

- The studies related to vibration of rotor systems due to rubbing are relatively small.

- Few studies have reported the analysis of parallel misalignment of shafts and its effects. This is the reason for introducing the newly designed pin type flexible coupling.

- Studies on unbalance are based on single rotor or two rotor systems. While those studies on unbalance of multi-rotor system and power (electricity) dissipation due to unbalance is rarely found in the literature.

- Most of the bearings are lubricated by grease only. Few works have been done on the effect of solid particles (contaminants) present in the grease lubrication system.

- In the literature, most of the bearing defects are identified by considering the Root Mean Square (RMS) values of the vibrations. But the other features viz. Maximum value, Overall RMS value, Mean Value, Variant, Kurtosis, Crest factor and Clearance factor are rarely used.

From the literature, it is evident that studies on fault diagnoses of bearings under various conditions are limited. Thus, a study of the vibration
signatures of bearings has become absolutely necessary. It can help greatly in identifying the faults for condition monitoring of bearings. Keeping these aspects in mind, the following are carried out in the present research work.

(i) Experimental study to identify a particular type of defect has been carried out. Specific defects are created artificially. Vibration signatures are obtained experimentally and are compared with theoretically computed fault frequencies.

(ii) Effect of rub on rotating shaft is attempted experimentally. Two rub materials; aluminium and mild steel; are tested against the mild steel shaft.

(iii) Effect of shaft misalignment and method of correcting the same is attempted both experimentally and numerically, using vibration signatures.

(iv) Methods of deducting the unbalance and correcting the unbalance in a CNC machine spindle system is attempted experimentally using vibration signatures.

(v) Effect of unbalance with mass addition or mass subtraction on a multi-rotor system on vibration and power consumption has been studied experimentally.

(vi) Use of Artificial Neural Network for identifying the defect and knowing the severity of defect using vibration signatures as input is attempted. Rotating machinery faults unbalance and misalignment is identified using ANN.

(vii) Effect of solid contaminants in a grease lubrication system is attempted systematically with a view to use the vibration signatures for condition monitoring.

The following chapters present them in details.