CHAPTER 02

LITERATURE REVIEW

Rolling element bearings are one of the decisive parts of any rotary machines. Life of any rolling element bearing depends upon some of the important parameters like operating conditions, quality of lubrication and presence of surface irregularity if any. These parameters are main sources of vibrations in the rotor bearing system. These vibrations affect the endurance strength of bearing leads to its failure in turn failure of machinery. The endurance life behavior has been presented by Franz Ebert [1] and described the necessary preconditions under which endurance life of bearing can be achieved. Chances of bearing failures are reduced and endurance life can be achieved by enlightening above mentioned parameters which affect vibration performance. Presence of surface irregularity in bearings is one of the most commonly observed parameters in failure analysis. Surface irregularities are categorized as local defects such as pits, cracks and dispersed defects like waviness, roughness etc. Huge study related to bearing failure analysis has been carried out by many researchers in last few decades. Some of the important diagnostic techniques such as vibration measurement, sound intensity, shock pulse method, stator current method and Acoustic emission technique etc. are reviewed by few researchers/Tandon et al, and Patil [2,3]. Accordingly, it was noted that vibration measurement is one of the most effective and widely used techniques for bearing failure analysis. Time domain analysis and frequency domain analysis are commonly carried out during vibration based condition monitoring of bearing. Frequency domain approach is indefinitely used as it gives severity as well as location of the defect.

Initialization of local defects is due to operating conditions, lubrication whereas distributed or dispersed defects are generally due to manufacturing fault. A detailed study of forces generated due to waviness in ball bearing is carried out by Wardle [4]. A model has been prepared by Choudhury and Tandon [5,6] for study of waviness in the races of roller bearing. The model predicts discrete spectrum with specific frequency components for each order of waviness. It also predicts that the amplitudes of spectral components due to outer race waviness were much higher as compared to those due to inner race waviness. If waviness is controlled during manufacturing then main source of vibrations are the local defects like pits, cracks produced due to
unhealthy operating conditions. The effort has been carried out by McFadden and Smith [7] and also by Choudhury and Tandon [8] in developing the model for single point local defect on the bearing races. The model incorporates the effects of bearing geometry, shaft speed, bearing load distribution and transfer function of vibration. Further, the model states that when a defect in one surface of a rolling element bearing strikes another surface, it produces an impulse which may excite resonances in the bearing and in the machine. As the bearing rotates, these impulses will occur periodically with a frequency which is determined uniquely by the location of the defect, be it on the inner race, outer race, or one of the rolling elements. Most of the above characteristics defect frequencies are keenly detectable from the fundamental running speed of the shaft. Value of these frequencies also depends upon bearing dimensions. Typical formulas have developed to calculate these frequencies.

Gunhee et al [9] present an analytical model to investigate vibration due to ball bearing waviness in a rotating system supported by two or more ball bearings, taking account of the centrifugal force and gyroscopic moment of the ball. The waviness of rolling elements is modeled by the sinusoidal function, and it is incorporated into the position vectors of the race curvature center. This research shows that the centrifugal force and gyroscopic moment of the ball plays the important role in determining the bearing frequencies, i.e., the principal frequencies, their harmonics and the sideband frequencies resulting from the waviness of the rolling elements of ball bearing. It also shows that the bearing vibration frequencies are generated by the waviness interaction not only between the rolling elements of one ball bearing, but also between those of two or more ball bearings constrained by the rotor. Further, the results of vibration measurements on roller bearings with simulated local defects have also been presented by Choudhury et al [10] at 1500 rpm to experimentally validate the theoretical model proposed. It can be observed from the results that the spectral components predicted by the theoretical model find significant presence in the experimental spectra. Comparison of the normalized analytical values of the spectral components with their experimental values shows fair agreement for most of the cases considered. Probable area of the generated excitation pulses has been calculated and the effects of pulse area variation on the experimental results have been studied.

Vibration monitoring of rolling bearing by High Frequency Resonance Technique was reviewed by McFadden and Smith [11]. HFRT was a topic selected by
author for the study which comprises the review of HFRT techniques carried out by earlier authors. Each stage of HFRT in the terms of success and failures was examined and approaches of each investigator were compared. McFadden et al [12] have studied two point defect model. In this paper, the original model is extended to describe the vibration produced by multiple point defects, thereby enabling large defects to be modeled by treating them as the sum of a number of point defects. The influence of multiple defects is explained by the reinforcement and cancellation of spectral lines because of differing phase angles. A comparison of predicted and measured spectra for a bearing with two point defects confirms satisfactory performance of the model. Some researchers Patil et al [13] have also prepared model for prediction of local defects. Prediction of amplitude becomes difficult because of the complex nature of system resulting from assembly of bearing elements and mounting of the same on the shaft and housing. With large defects and medium operating speeds, most methods of detection works satisfactorily but at low speeds with small defects, problems arise. Smith [14] describes work on measurements at low speeds and discusses the difficulties which arise. The results have demonstrated that each one of these techniques is useful to detect problems in roller bearings. However, very little research has been done to correlate the amplitudes of these spectral components at higher speed with the extent of defect, though such a correlation will be of huge help for diagnostic purpose. H. Arslan et al [15] have carried out an investigation of rolling element vibrations caused by local defects at higher speed. The model is prepared by assuming the races as a springs and balls as mass. Obtained results showed that it was possible to identify the defected element of ball bearing by studying ball vibrations using the simulation model.

Tandon [16] have compared some of the vibration parameters used for detection of the defects in rolling element bearings. Overall RMS, ceptrum, crest factor and peak of acceleration signal of bearing with defects of different sizes are compared with those of healthy bearings. The results of measurement indicate that, except crest factor, all the parameters have detected the defects in the bearings. The defect detectability of overall power is best followed by peak and RMS measurement. Experimental results were also obtained by few of the authors Botsaris et al [17] successfully for vibrations produced by rolling element bearings at moderate speed. A preliminary estimation of the most common analysis methods of the vibration signals of a ball bearing is tried. The tested methods are the typical statistic analysis method, the Fourier transform, the frequencies spectrum analysis and the Wavelet method.
Mohamadi et al [18] described the suitability of vibration monitoring and analysis techniques to detect defects in roller bearings. Triaxial vibration measurements were taken at each end of the coupling on the motor and rotor bearing housings. The results indicate that bad bearing has a strong effect on the vibration spectra. Time domain analysis, vibration spectrum analysis have been employed to identify different defects in bearings. The results have demonstrated that each one of these techniques is useful to detect problems in roller bearings.

Different case studies were carried out by Sadettin et al [19] to monitor the vibrations of huge centrifugal pump. In this study, diagnosing techniques of the ball and cylindrical roller element bearing defects were investigated by vibration monitoring and spectral analysis as a predictive maintenance tool. Ball bearing looseness, a ball bearing outer race defect and a cylindrical bearing outer race defect were successfully diagnosed. It was shown that ball and cylindrical roller bearing defects were progressed in identical manner without depending on rolling element type. Furthermore, it was experienced that when a bearing defect reaches an advanced stage, high frequency amplitude levels often decrease due to self-peening of the bearing flaws.

Time and frequency domain analysis was carried out by Amarnath et al [20] during condition monitoring of antifriction bearings. Time waveform indicates severity of vibration in defective bearings. Frequency domain spectrum identifies amplitudes corresponding to defect frequencies and enables to predict presence of defects on inner race, outer race and rollers of antifriction bearings. The distinct and different behavior of vibration signals from bearings with inner race defect, outer race defect and roller defect helps in identifying the defects in roller bearings. White [21] has given emphasis on vibration signature characteristics by study of load distribution function. Formation of load zone depends upon diametral clearance and load distribution factor. When defect is out of load zone, it does not give response to the sensor. Many other techniques have also been attempted for defect detection. Yadav et al. [22] have compared different condition monitoring techniques for detection of the defects. It includes sound measurement, shock pulse measurement and stator current technique. It was concluded from their study that vibration analysis is most effective technique. Some of the other supporting techniques were also adopted by many of the researchers for condition based monitoring. T Igarashi [23] have carried out studies on the vibration and sound of defective rolling bearing and concluded that vibration analysis is the best technique.
Chinmay Kar et al[24] mainly discussed the applicability of Kolmogorov–Smirnov (KS) Test as a means of bearing fault diagnosis. The KS Test is carried out among the bearings to make a standard control group. It has been found that any defect in a ball bearing has a specific distribution, and hence can easily be distinguished from the good bearing with certainty. The effects of ball groupings on the pitching and yawing ball passage vibrations of linear guide way type ball bearings (linear ball bearings) under low-speed operation were studied by Hiroyuki Otha et al[25]. The experimental and calculated results show that the occurrence of the pitching and yawing ball passage vibrations was affected by the ball groupings. Root Cause Failure Analysis of Outer Ring Fracture of Four-Row Cylindrical Roller Bearing was carried out by H Hirani [26]. In the present study, a visual examination of failed rolling surfaces has been emphasized. An analytical approach has been utilized to determine the maximum load on the roller and the outer ring raceway interface.

Bearing fault modes and their effects on the bearing vibration are discussed by Bin Zhang et al[27]. Based on this, a feature extraction method is developed to overcome the limitation of time domain features. Experimental data from bearings under different operating conditions are used to verify the proposed method. Authors concluded that the extracted feature has a monotonic decrease trend as the dimension of fault increases. The feature also has the ability to compensate the variation of rotating speed. The proposed structures are verified with three different detection routines, pdf-based, k-nearest neighbor, and particle-filter-based approaches. The effect of radial clearance, number of rollers and viscosity on the bearing noise was examined by Byoung-Hoo Rho et al [28]. It was concluded from their study that the fundamental frequency of the noise components of the cylindrical roller bearing corresponds to the multiplication of the number of rollers and the whirling frequency of the roller center. The purpose of this article is to numerically investigate one source of acoustic noise in roller bearings that results from the motion of the rollers in the bearing under zero external load. For the sake of simplification, it was assumed that the cylindrical roller bearings are infinitely long. Furthermore, the effects of the following on the noise of the bearing were also examined: the radial clearance of the bearing, the viscosity of the lubricant, and the number of rollers. The results of the study show that the fundamental frequency of the noise components of the cylindrical roller bearing corresponds to the multiplication of the number of rollers and the whirling frequency of the roller center. The Application of sound intensity technique to defect detection in rolling Element
Bearing was focused by Tandon and Nakira [29, 30]. An experimental investigation of grease lubricated bearings with contaminated grease was carried out by Xiaobin Lu et al [31]. A series of experimental results is presented to explore the frictional characteristics of a grease-lubricated journal bearing. Load, grease type, and bushing material are varied to examine their effects on the friction coefficient. The results attest to the existence of distinctive regimes in grease lubrication akin to the oil-lubricated Striebeck curve.

Lubrication is an important parameter for smooth working of the bearings. Majority of part of all rolling bearings are lubricated with grease. N Tandon et al [32] have used different techniques for condition monitoring bearing lubricated with contaminated grease. The vibration, stator current, acoustic emission and shock pulse method measurements performed on lubricant contaminated bearings are appreciably increased as contaminant level and contaminant size increased. The contaminant level increase with constant size has shown less increase when compared to particle size increase with constant contaminant level.

Pavle et al [33] studied that the detection of improperly lubricated bearings from vibration patterns is a difficult task especially when records from short operating periods are available. This is exactly the case of end-quality assessment systems. This problem has been addressed by applying both cyclostationary analysis and spectral kurtosis for the selection of a frequency band in which variations in vibration patterns are most expressed. The approach was evaluated on a test-set comprising 63 electrical motors with fault-free and 21 with improperly lubricated bearings. The results reveal that improper lubrication is expressed as increase in the spectral components at bearing cage and ball spin frequency. Some other techniques are also studied and compared with vibration analysis by several researchers. L. M Rogers [34] describes the detection of incipient failure of rolling element bearing by kurtosis and location of fatigue cracks in slowly rotating bearing by acoustic emission technique. The typical bearing selected for the experiments was a slew ring which is large diameter heavily loaded antifriction bearing. Online measurements were carried out on cranes and noted that there was little difference between amplitude distributions recorded when crane was of load and when it carried a four ton load. Further, the detailed review of vibration and acoustic emission technique (AET) was carried out by Tandon and Nakira [35, 36] during the condition monitoring of rolling element bearings.
They have also compared the effectiveness of both the techniques and concluded advantages and limitations of both the techniques. According to their study AET gives early prediction of the defect but it is very difficult to process the acoustic signals. Vibration analysis is commonly adopted and easy process to monitor the condition of rolling bearing. The usefulness of acoustic emission (AE) measurements for the detection of defects in roller bearings has been investigated by Choudhury and Tandon [37]. Defects were simulated in the roller and inner race of the bearings by the spark erosion method. AE of bearings without defect and with defects of different sizes has been measured. For small defect sizes, ring down counts of AE signal has been found to be a very good parameter for the detection of defects both in the inner race and roller of the bearings tested. However, the counts stopped increasing after a certain defect size. Distributions of events by ringdown counts and peak amplitudes are also found to be good indicators of bearing defect detection. With a defect on a bearing element, the distributions of events tend to be over a wider range of peak amplitudes and counts. N Hamzaoui et al [38] carried out theoretical modelling which consists in developing a vibro-acoustic calculation of a rotating rotor on bearings with a numerical simulation of mechanical defects. This paper presents the experimental study which was obtained for a test bench composed of three supports "motor, rotor on bearings and speed reduce in order to simulate such mechanical defects. Comparisons between theoretical and experimental results are presented.

Eric y Kim et al [39] presented an experimental evaluation for incipient fault detection of low speed REBs by using an acoustic emission (AE) sensor and an accelerometer. A low speed fault simulation test rig was developed to simulate common machine faults with shaft speeds as low as 10rpm under loading conditions. Tests were conducted on the rig with various seeded defect bearings. This study reveals the best frequency bandwidth and suitable parameters for condition monitoring using AE signal for early detection of low speed bearing defects by means of statistical parameters in time domain. Along with bearings, AET can be also be adopted for condition monitoring of other rotary parts such as pumps, gear boxes and engines. D Mba et al [40] presented a comprehensive and critical review on the application of AET to condition monitoring and diagnostics of rotating machinery. AE was originally developed for non-destructive testing of static structures; however, over the last 35 years its application has been extended to health monitoring of rotating machines, including bearings, gearboxes, pumps, etc. It offers the advantage of earlier
defect/failure detection in comparison to vibration analysis due to the increased sensitivity offered by AE. However, limitations in the successful application of the AE technique for monitoring the performance of a wide range of rotating machinery have been partly due to the difficulty in processing, interpreting, and classifying the intelligent information from the acquired data. The main drawback with the application of the AE technique is the attenuation of the signal, and as such the AE sensor has to be close to its source.

Further, D Mba [41] reviewed current methodologies of applying acoustic emission (AE) technique for bearing failure analysis. Investigation of Mba focused on validating already established AE techniques and establishing appropriate threshold level for AE counts for bearing failure analysis. Discrete wavelet-based thresholding study on acoustic emission signals to detect bearing defect on a rotating machine was presented by Yanhui Feng et al[42]. In this paper, Acoustic Emission signal denoising problem is studied based on Discrete Wavelet Transform thresholding methods. The denoised Acoustic Emission signals allow detection of the defect and identification of the type of bearing defect. The spectral distribution function is used by Davis [43] to characterize the vibration signal of rotating machinery. It is shown to be a more robust indicator than conventional power spectral density estimates, but requires only slightly more computational effort. The method is demonstrated with a model of a defective bearing. The spectral distribution function is applied to practical problems involving seeded helicopter transmission faults and the vibration signal from a ground-based vacuum compressor system. A running torque analysis was performed by Masayuki Kanatsu [44] on axially loaded, deep groove ball bearings lubricated with a polymer lubricant. The analysis was applied to two types of bearings. The analysis was applied to a 6206 deep groove ball bearing axially loaded in a range typical of preloads applied in actual application to this size bearing to establish bearing tare torque. The results were compared to an available database. A three-dimensional dynamic simulation analysis of a tapered roller bearing was performed by Tomoya S et al [45] using commercially available software. Without cage pocket shape simplification, the dynamic motion of the cage and rollers was calculated in six degrees of freedom. The motion of the cage and rollers was measured experimentally to verify the analysis. Under all axially loaded conditions, cage whirl was analytically predicted and experimentally confirmed. Whirl amplitude increased as the inner-ring rotational speed and axial-load magnitude increased. The maximum whirl amplitude reached the radial
clearance between a roller and its pocket. N Sawalhi presents [46] an algorithm to enhance the surveillance and diagnostic capability of SK as an analysis tool for rolling element bearings, by combining it with the use of AR-based linear prediction filtering and MED. The use of the MED along with SK analysis also greatly improves the results of envelope analysis for making a complete diagnosis of the fault and trending its progression.

Won Pyo Hong et al [47] addresses experimental results for diagnosing faults with different rolling element bearing damage via motor current spectral analysis. This paper takes the initial step of investigating the efficacy of current monitoring for bearing fault detection by incipient bearing failure. The failure modes are reviewed and the characteristics of bearing frequency associated with the physical construction of the bearings are defined. The effects on the stator current spectrum are described and related frequencies are also determined. Further Har-Prasad [48] reports the cause of generation of localized current in presence of shaft voltage. Also, it brings out the developed theoretical model to determine the value of localized current density depending on dimensional parameters, shaft voltage, contact resistance, frequency of rotation of shaft and rolling-elements of a bearing. Furthermore, failure caused by flow of localized current has been experimentally investigated. Wavelet analysis provides multi-resolution in time-frequency distribution for easier detection of abnormal vibration signals. From the extensive experiments performed [49-52] in a series of motor-pump driven systems, the methods of wavelet analysis and FFT with ED are proven to be efficient in detecting some types of bearing faults. Since wavelet analysis can detect both periodic and non periodic signals, it allows the machine operator to more easily detect the remaining types of bearing faults which are impossible by the method of FFT with ED. Hence, wavelet analysis is a better fault diagnostic tool for the practice in maintenance. Many of the other techniques were also adopted successfully by some of the researchers for bearing fault diagnosis. These are Transient Rotor dynamic Modeling [53], HMM-Based Fault Detection and Diagnosis Scheme [54] and the combination of genetic algorithms and fast kurtogram [55]. A roller bearing fault diagnosis method based on EMD energy entropy and ANN was put forward by Yang Yu et al [56]. The analysis results from roller bearing signals with inner-race and outer-race faults show that the diagnosis approach based on neural network by using EMD to extract the energy of different frequency bands as features can identify roller bearing fault patterns accurately and effectively and is superior to that based on wavelet packet
decomposition and reconstruction. D M Shamine [57] presented the in-situ experimental identification results of bearing dynamic joint parameters in actual machine tools. An in-situ FRF-based identification, which includes indirect estimation of unmeasured FRF’s, was implemented for determining bearing joint parameters in actual spindle systems.

Apart from all these studies by vibration and acoustics, the condition based monitoring can also be carried out by other techniques such as root cause failure, Genetic algorithm, wavelet transforms and Artificial Neural network. Some statistical studies and simulation techniques are also carried out by few researchers. A simulation technique is proposed by Zeki Kiral et al [58] to simulate the vibration of bearing structures which houses a ball bearing with or without a defect. These authors have developed a program to model the dynamic loading of the bearing structure, considering the bearing kinematics and load distribution. A force model is proposed to simulate the impulse force which arises at ball-defect impact. The nodal excitations in time domain are defined as an input to a commercial finite element package. Xinwen Niu et al [59] presents some new statistical moments for the early detection of bearing failure. The third moment, skewness, of the rectified data or the fourth moment, kurtosis, of the unrectified data, has been the major statistical parameter for monitoring the condition of the rolling element bearing. A novel and unified description of normalized statistical moments is proposed. In the formula, the orders of the moments are real valued, providing more flexibility for field operation.

The summary of literature is as given in Table 2.1.

Summary

After the exhaustive literature survey, it is observed that vibration analysis is one of the most effective tools to monitor the condition of rolling bearings. It is also clear that most of the work carried out is at shaft speed ranging from 60rpm to 1500rpm. Most of the techniques of defect detection work smoothly at moderate speed and moderate defect size but problem arises at higher speed and for large defect size. The present work focuses on vibration analysis of faulty deep groove ball bearings with smaller to larger defect width at comparatively higher speed up to 5000rpm. The previous work in the literature was focused on the cantilever arrangement for loading on the bearing and also not validated by numerical methods i.e. using ANSYS. Taking this in to consideration, the present work is continued by developing the mathematical
model for single row deep groove ball bearing mounted on simply supported shaft where as the earlier models are based on cantilever position which is rarely observed in the present scenario. Further the theoretical results are validated with numerical method using ANSYS LS-DYNA package and by experimental method by actual measurements of vibration amplitudes on high speed test rig. The theoretical, numerical and experimental results are compared at various conditions of speed, load and defect sizes.

<table>
<thead>
<tr>
<th>Sr.No</th>
<th>Authors</th>
<th>Journal and Year</th>
<th>Particulars of work</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>J D Smith</td>
<td>Tribology international, 1982</td>
<td>Ball bearing with defect size of 0.02mm to 0.05mm was rotated at Speed 60rpm with load 200kg.</td>
</tr>
<tr>
<td>2.</td>
<td>Mc Faddan, J D Smith</td>
<td>Jr. of sound &amp; Vibration, 1984</td>
<td>Ball bearing with defect size of 0.5mm on inner ring was rotated at Speed 600rpm with load 50kg.</td>
</tr>
<tr>
<td>3.</td>
<td>N Tandon</td>
<td>Measurement, Elsevier, 1995</td>
<td>Ball bearing with defect size of 0.05mm to 0.5mm was rotated at Speed 1500rpm with load 50kg.</td>
</tr>
<tr>
<td>4.</td>
<td>A Choudhury, N Tandon</td>
<td>Jr. of sound &amp; Vibration, 1997</td>
<td>Roller bearing with defect size of 1.5mm on inner was rotated at Speed 1500rpm with load 50kg.</td>
</tr>
<tr>
<td>5.</td>
<td>Sadettin Orhan</td>
<td>NDT &amp; E international, 2005</td>
<td>Ball bearing was rotated at Speed 2000 rpm with load 50kg till initialization of crack.</td>
</tr>
<tr>
<td>6.</td>
<td>Arslan, Akturk</td>
<td>Jr. of Tribology, Oct-2008</td>
<td>Ball bearing with defect size 0.5mm was rotated at Speed 5000rpm with load 1kg.</td>
</tr>
<tr>
<td>7.</td>
<td>Mohamadi Monavar</td>
<td>World applied Science, 2008</td>
<td>Roller bearing was rotated at Speed 500rpm with load 60kg.</td>
</tr>
<tr>
<td>8.</td>
<td>M S Patil, J Mathew</td>
<td>Int. Jr of Mechanical Science, 2010</td>
<td>Ball bearing with defect size 0.05mm to 1.5mm was rotated at Speed 1200rpm with load 10kg.</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of Literatures