RECENT APPROACHES AND MEASUREMENT TECHNIQUES FOR THE BEARING FAULT ANALYSIS – A REVIEW

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ABSTRACT

In recent years manufacturing sector uses different types of motors for its production of parts and components. Majority of machining applications uses induction motors, single phase motors for light duty application and three phase motor for heavy duty application. The need for the industry is to run the motors failure free so that the production capacity is meet out. To achieve this, motor components has to perform trouble free operations, but in a due course of time when the motors are made to run for a longer period of time, it develops wear among the parts. When considering the faulty parts bearing wear is one major issue. Due to this the motor also gets damaged, if this happens the entire motor has to be repaired or replaced. Many fault detections methods and techniques have been implemented; different methods of bearing fault identification are being conducted. Here a detailed review about bearing fault analysis and its recent developments are described in this paper.

Keywords: induction motors, bearing fault identification


1. INTRODUCTION

In any rotating machinery ball bearing is an important component. Most of the mechanical hardware and motors uses ball bearings, which gives a supporting mechanism for the machineries. The ball bearing makes the motor or any rotating machinery to run smoother with minimal friction and mechanical losses in its movement. If the ball bearing runs smoother then there won’t be any vibration or defects in it. Hence, fault diagnosis using vibration has become
major contributing area and reported more number of [1–4]. Due to presence of noise in the data measured, difficulties raised in bearing fault diagnosis from vibration signal analysis [5, 6]. Hence, de-noising the acquired vibration signal become more important in the area of signal conditioning and fault diagnostics using vibration signal [6,7]. Whenever bearing is used for longer period of time it starts developing internal wear, cracks, and hardening of the grease and develops vibration in the bearing which results in wear of the rotating machinery. Due to this reason the ball bearing in rotating machinery has to be replaced over a period of time. Some methods have to be implemented to identify the defects caused in the ball bearing, so that the rotating machinery does not get damaged by ball bearing. Many researches are exploring in depth identification of bearing defects. Due to dynamic load, speed and external interference detection of bearing faults operated in variable frequency drives becomes challenging [2]. Some of the methods like time domain analysis, frequency analysis, wavelet transform, spectral analysis, vibration and current monitoring are implemented in ball bearing analysis. This paper gives a review of the various recent ball bearing defect analysis methods and techniques.

The common ball bearing defects are inner race defect, outer race defect, ball bearing defect, hardening of grease and the vibration caused by it. From the reviewed papers few methods have been classified which can give a detailed study on it. The following are the methods which can detect the above mentioned defects.

- Time domain analysis
- Frequency domain analysis
- Vibration analysis
- Wavelet transform
- Spectrum analysis
- Current monitoring and
- Mathematical Modelling

Figure 1. (a) Rolling element bearing and (b) Internal view shows the parts of ball bearing [10].

1.1. Time & Frequency domain analysis:
Reza Golafsha, et al., [7] has analysed the fault signature modelling and detection of inner race bearing faults in their paper on “SVD and ‘Hankel’ matrix based de-noising approach for ball bearing fault detection and its assessment using artificial faults”[1]. In this method, Singular Value Decomposition (SVD), analyze the peak spectra using the phase coupled sidebands occurring at spacing, has been predicted in this model. First the fault signature magnitude and
load is tested. The results of the test consist of the machine vibration due to the radial movement of the bearing, air gap variation due to relative motion between the raceways, variation in rolling resistance due to load torque. The ball bearing radial movement confirms the machine vibration with a faulty frequency. The measurements are taken through vibration transducers. From the results a model is developed with time domain convolution of white noise with that of the mechanical frequency response of the mechanical function [1].

![Diagram of Ball Bearing with Downward Radial Load](image-url)

**Figure 2.** Shown in the above figure is: downward radial load applied to the inner race of four bearing surfaces as well as the resulting load zone [1].

To a large extent, the magnitude of this radial movement depends on the magnitude of radial load applied to the inner raceway. Bearing illustrated in fig. 2. Shows, defect impact causes a minimal effect in a rolling element, in the absence of radial load. This is because of racial separation between the inner and outer raceways maintained in the neighboring rolling elements and is able to pass over the defects. However, rolling element exhibits elastic deformation under application of a radial load and experiences a compressive force. This forces rolling element into the defects and causes impact effect. It also increases the inner race defects due to race way and rolling element couplings. When the characteristic fault frequency of inner-race is an integer multiple of rolling element characteristic frequency the rolling elements are easy to identify. Hence the defects identification in rolling element or cage, this model is can be easily extendable. Xiaoxi Ding.et.al.[3], proposed time-frequency manifold reconstruction of sparse method as a transient method for identifying the bearing fault features. From this method reconstruction of image sparse is computed with analysis framework. The transient characteristics of signal from low signal-to-noise ratio (SNR) are studied in this model. Time-domain averaging method [4], band-pass filtering [5], frequency-domain thresholding [6], empirical mode decomposition (EMD) [7], wavelet transform (WT) [8], time–frequency analysis (TFA)[9] are various denoising methods reported for fault signature extraction.

However, in acquired signals, the presence of background noise affects the fault diagnosis and causes difficulty in fault diagnosis. This makes incapability in fault analysis; it makes the denoising process one of the most essential steps in signal condition monitoring and fault identification. This study reports de-housing process with Singular Value Decomposition (SVD) and ‘Hankel’ matrix successfully applied to vibration analysis of ball bearing in time domain spectrums for the elimination of the background noise and the improvement there liability of the fault detection process. The effectiveness of this method is compared experimentally as well as
the simulated vibration signal tests conducted confirmed this de-housing approach suitability for the fault identification in ball bearings.

*S.A.McInerny et.al. [10]*, describes a laboratory module on fault detection in rolling element. This module considering the basic operational characteristics of bearing element also provided theoretical formulas for fault characteristic frequencies. Detection of bearing faults is carried out using conventional spectral analysis of generated vibration signals using program developed in MATLAB. This generated vibration signals includes important signatures obtained in bearing housings. Also, described the inter relationship between fault signatures of bearing and amplitude modulation and demodulation with the support of envelop analysis. Graphical user friendly interface (GUI) software utilities developed in MATLAB allows exploring envelope analysis using measured data / the generated signal. With GUI utilities obtained spectra with Hanning window implemented FFT and user selectable parameters. In this method the envelop data has bandwidth half of the acquired data, hence the enveloped data down sampled by a factor of 2 prior to spectrum analysis. The fault frequency of bearing and it’s harmonics are clearly visible in the final processed spectrum.

1.2. Vibration Analysis:

Vibration analysis is one of the most powerful tools for the bearing fault detections. It would be a simple process if noiseless vibration signatures are measured on bearings to identify fault in it. But practically the acquired vibration signals from bearing element and it’s housing, buried in noise due to random vibration caused by friction, misalignments and imbalances. These random vibrations dominate the fault signature in the measured spectrum and actual expected vibration spectrum are lost in the higher harmonics and its spectral noise floor.

Bearing failure occurs due to several mechanisms, including damages caused by mechanical, crack, wear, lubricant deficiency, and corrosion [3]. Nicks and dents are due to abusive handling of berating elements. When higher stress on the contact impair the smooth surface, i.e., marred and reduces the life time of bearing element drastically. ‘Brinelling’ is another harmful condition caused in rolling element due to its overload. Cyclic loading and over loading create crack in bearing, manufacturing defects also leads to crack. In a bearing element gradual deterioration due to wear leads to dimensioning related faults. Normally metal-to-metal friction occurs and increases due to inadequate or poor lubrication also increases the temperature of the bearing element, reduces bearing life time. Plastic deformation occurs due to operating forces. Scuffing or scoring is lighter adhesive damage; sizing or galling is highly intense damage. Abrasive wear occurs if any hard particle intervene the smooth contact surface. Higher humidity environment due to surface oxidation produce rust and pits and raises the stress and ultimately leads to abrasion and rapid wear. In an example of an outer race of a ball bearing is flawed because of one of the failure mechanisms in which one of the balls rolls over the flaw, an impulsive force is incurred that causes the bearing to vibrate. The bearing responds by “ringing” at its Fig. 3.
Four characteristic frequencies are given here under of a rotating bearing element in which the outer race is stationary and its rotating inner race.

Train Frequency or Cage Frequency (FTF)

$$FTF \ (Hz) = S (1/2) \ (1 - B/P \ Cos \ \phi) \quad (1)$$

Ball pass frequency, Outer race (BPFO)

$$BPFO \ (Hz) = S (N/2) \ (1 - B/P \ Cos \ \phi) \quad (2)$$

Ball pass frequency, Inner race (BPFI)

$$BPFI \ (Hz) = S (N/2) \ (1 + B/P \ Cos \ \phi) \quad (3)$$

And Ball Spin frequency (BSF)

$$BSF \ (Hz) = S (P/2B) \ (1 + B^2/P^2 \ Cos^2 \ \phi) \quad (4)$$

Where $B$ is ball diameter, $P$ is pitch diameter, $N$ is number of balls, and $S$ is rotation rate of the shaft (in hertz). But in thrust load condition the characteristic frequencies have some slippage and needed appropriate correction factors. For these purpose software modules incorporated required correction parameters are available commercially [11].

With the above theoretical calculations attempts were made to identify the characteristic frequencies of bearing under test [10]. In this work a synthetic signal was constructed with a square wave approximation and random noise, ringing pulse sequence and their sum has been carried out and obtained simultaneous spectra and composite waveform. But in this analysis, the higher harmonics in pulse sequence spectrum higher harmonics in the spectrum disappearing slowly compared to square wave approximation. The peaks in the composite signal spectrum are lost. Finally they used band pass filtering in “envelope analysis” rejects the high-amplitude low-frequency signals associated with misalignment and imbalance to eliminate random noise [8, 9]. Analyzers and data loggers used in envelope analysis usually have user selectable band pass settings of required frequencies. Final step in the envelope analysis process is calculation of the spectrum of the rectified band pass filtered signal with Hilbert transform. In this work the software utility developed in graphical user interface (GUI) with MATLAB utility for the envelope analysis.
1.3. Spectrum Analysis

In S.A. McInerny et.al. Report [10], bearing fault frequency and its harmonics are distinctly visible in the spectrum obtained with MATLAB based graphical user interface (GUI) program. This confirms effectiveness of this spectrum analysis method in bearing fault deduction analysis.

J.J. Jayakanth et.al., [13], brings out the very simple way of detecting bearing faults, that too in a static condition, as a first time, using impulse excitation technique and implemented with power spectrum in LabVIEW graphical user interface (GUI) program with the graphical icon auto computed FFT Power Spectrum module. In which acquired vibration signal from MEMS accelerometer as a function of time, is auto computed online Power Spectrum (PS) through LabVIEW Palette (i.e., Power Spectrum.vi), for 10 impulses to the bearing under test, computes the averaged auto power spectrum of acquired time signal from MEMS accelerometer.

The power spectrum provides clear signature of faulty and good bearing in any size or make of tested bearings. Since it reflects the energy spent by fault bearing is larger compared to the smooth and lesser energy consumed good bearing for the given excitation, i.e, for an impulse. Defective bearings increase the amplitude of the peaks in the power spectrum after FFT is carried out which indicates the presence of the defect (as shown in fig.5).

Figure.4. GUI based data processing flow diagram of Envelop Analysis with MATLAB utilities [10].

Figure.5. (a) Acquired Vibration Signal from MEMS Accelerometer for excited impulses, (b) Auto computed FFT Power Spectrum acquired Vibration Signals in LabVIEW for two bearings of same size and make [13].
1.4. Wavelet transforms:

S.Khanam.et.al. [14] diagnose fault analysis of bearing and access its severity using wavelet technique. Generally speaking limited duration waveforms are called wavelets, in wavelet analysis breaking up of a signal into shifted and scaled versions of the original wavelet that has an average value of zero [15]. Wavelets are ideal tool for analyzing transient signals and provide time-scale information and facilitate extraction of varying parameters with respect to time. Wavelets transform are of two types, viz., continuous and discrete. Convolution of signal and wavelet function calculation is involved in continuous wavelet transform A wavelet function is a small oscillatory wave contains both the analysis and the window function. In discrete wavelet to extract the genuine frequency content of the signal in various sub bands filter banks are used, for signal analysis and synthesis. To reduce the computational time, discrete wavelet transform is derived from continues wavelet transform discretization by adopting dyadic scale and translation [16].

\[
DWT (j, k) = \frac{1}{\sqrt{2^j}} \int_{-\infty}^{\infty} s(t) \psi^*\left(\frac{t-2^j k}{2^j}\right) dt
\]

Where \(j, k\) are integers, \(2^j\) and \(2^j k\) are the scale and translation parameter respectively, \(\psi\) is the ‘mother’ wavelet and \(\psi^*\) is the complex conjugate of \(\psi\). The signal \(s(t)\) to be processed passes through low pass and high pass filters emerging as low frequency and high frequency signals (with approximations \(a_i\) and details \(d_i\) respectively) at each decomposition(of level ‘n’).

Therefore, signal \(s(t)\) can be written as [17]

\[
S(t) = a_0 + \sum_{i=1}^{n} d_i
\]

Daubechies [15] proposed ‘Symlets’ supported wavelets with least asymmetry and highest number of vanishing moments for a given support width, associated scaling filters are near linear-phase filters, which make them easier to deal with small discontinuity present in the signal without affecting the original information. The continuous and discrete wavelet transform uses this approach due to its perfect reconstruction and cancellation capability. The sym5 wavelet based decomposition gives raise defect size indication by precisely locates leading edge and trailing edge impacts. The outer race defect size of the bearing element can be evaluated by recording the raising (entry event) and trailing edge (exit event) of the signal after decomposition for the sym5 wavelet. The following equation provides information about size of the defect using duration between set of events at the leading and trailing of the defect edge:

\[
\text{Defect size} = r_b \times \omega_b \times \Delta t = \frac{D_p \rho_s}{4} \left(1 - \frac{d_b^2}{D_p^2} \cos^2\alpha\right) \times \Delta t
\]

Where \(r_b\) is radius of the ball, \(\omega_b\) is the ball spinning speed, \(\omega_s\) is the rotational speed of shaft, \(D_p\) is the bearing pitch diameter, \(d_b\) is the diameter of the ball, \(\alpha\) is the deep groove ball bearing’s contact angle equal to zero and \(\Delta t\) is the duration between the raising and trailing impact pulse.

S.Khanam.et.al.,[14] have been performed experiments with an accelerometer using an undamped natural frequency for acquiring the vibration signal using accelerometer mounting on the top of test bearing housing. The captured signal was stored in Fast Fourier Transform (FFT) Analyzer and transferred to an intelligent processor system where the post processing was carried out in the MATLAB environment. Experiments have been performed at user selectable shaft rotational speed of and radial load. With varying size of the defect on the outer race of the test bearing, random for the healthy case, periodic impulses generated as the ball passes over the defect at a rate equal to characteristic defect frequency were observed experimentally. So the impulses in the high frequency range of wavelet decomposition are covered in initial decomposition. An average of the data points between the two events for all the bursts present in
the signal enable to obtain bearing outer race defect size precisely by time interval between two subsequent events.

The decomposition of the vibration signal using Symlet wavelet measures precisely the fault size on the ball bearing outer race. The bearing fault less than the ball diameter with significant depth has peak at leading edge and at trailing edge. The ball contact with the base generates multiple events due to shallow faults. These measurements of defect sizes are verified with optical microscope confirm the technique: a way easier and precise estimation bearing fault size.

Wavelets are competent tool for bearing fault diagnosis [18-24], due to its efficient computational implementation and flexibility. Main implementation of wavelets in bearing fault diagnosis by Peng and Chu [18] involves time frequency signal analysis, demising and extraction of the weak signal, fault feature extraction, singularity detection, compression of vibration signal and identification of system. Discrete wavelet transform are used in Prabhakar et al. [19] to detect and identify single, multiple and combination ball bearing race faults. Shi et al. [20] uses wavelet transforms and envelop spectrum for extracting bearing defect signatures. ‘Morlet’ wavelets are used for demodulating defect components in the bearings in Nicolaou et al., [21] work. Qiu et al. [22] reported a comparison of de-noising with wavelet filter and of de-noising with wavelet decomposition and concluded that wavelet filter based de-noising and wavelet decomposition based de-noising with the conclusion that wavelet filter based de-noising is finding its suitability in weak signature detection. Junseng et al. [23] reported the extraction of bearing fault features from vibration signals by constructing impulse response wavelet in continuous wavelet transform. The recent work by Kumar et al. [24] reported signal decomposition using ‘Symlet wavelet’ for the extraction of outer race of taper roller bearing fault size. The confident applications of ‘Symlet’ wavelets in many other fields are reported in literature Literatures like noise reduction from ECG signals [25] and speech signal de-noising [26].

1.5. Kurtosis coefficient a Time-Domain Statistics:

From the time domain data, vibration signal, evaluation of kurtosis coefficient [27-30] is effectively used in the bearing fault detection. A zero mean signal, variance, \( \sigma^2 \), is the mean square value [i.e., the square of the root-mean-square, RMS value] of an AC coupled accelerometer signals are zero mean signals. Its rectified waveform has a nonzero average or mean value. In this case, the variance is given by

\[
\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (x(t_i) - \mu)^2
\]

Where \( N \) is the number of data points in the data sequence, and \( \mu \) is the average value. The kurtosis coefficient is a fourth-order statistic normalized by the square of the variance \( \sigma^2 \)

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

This statistical moment is sensitive to the pulses induced by bearing defects and effective in the rolling element bearing diagnostics.

The localized defects in the bearing element outer race, inner race and rolling element cause faults in rolling element or the cage, which generates impacts and impulse and excite the total system including bearing, sensor mounted on it and beating housing. The characteristic frequencies of bearing elements and its order can be identified by using signal processing techniques.

A de-convolution and de-noising technique is reported in Lianhuan Hong et al. [31] As a maximum correlated adaptive ‘kurtosis’ de-convolution and multi wavelet transform. In this paper This paper propose a compound fault analysis combined with Hilbert envelope spectrum analysis based on maximum correlated ‘kurtosis’ de-convolution theory. a parameter range
estimation method is given for its parameter optimization. Standard flexible multi wavelets are used in signal post processing to enhance the de-noising effect. An M-shift correlated kurtosis composed fault characteristics index with square envelop spectrum entropy is used to construct, particle swarm optimization based, customized multi wavelets. The usefulness of this method is demonstrated by both simulated signal and practical vibration signals of a rotor in an experimental rig with different compound faults. The reliability and superior effectiveness of this method are confirmed by comparison with other fault detection methods.

1.6. Current monitoring:
S.Mitra et.al [32] Carried out comparative measurements on fault bearing analysis with three different techniques say: current monitoring technique, sound signal technique and vibration analysis technique. In its work using current clamp, three phase induction motor current signal was recorded. Audible sound or noise of the machine also measured using standard digital sound level meter kept near motor under test. An accelerometer with sensitivity of 1 mV/g, and bandwidth of 2 kHz was kept on the top the motor with to acquire the vibration signal. Fig.6. shows the acquired spectrum of the current, vibration and sound sensors.

![Frequency as function of power spectral density plot](image)

**Figure.6.** Frequency as function of power spectral density plot of the (a) motor current signal (b) sound signal acquired (c) vibration amplitudes of rotating bearings when the mixer motor (under load) in the presence of external noise [32].

In the comparative study, it has been reported first, the current signals are too weak, hence the fault identification is too difficult in real time background, hence, it is really a challenging to identify healthy and faulty bearings. Fault identification with acoustic and vibration signals techniques are reasonably good compared to current monitoring technique.. Mounting acoustic microphone also very simple than the vibration sensors, but artefact effect due to outside noise in acoustic method is very much sensitive and affects the actual measurements. Hence it confirms, vibration signals technique dominates the other methods for fault identification of the industrial actuators.
1.7. Mathematical models:

Nabhan.A.et.al. [33] developed a mathematical model for the ball bearing defect analysis and vibrations due to defect on the bearing race. Using a commercial package ABAQUS/CE, investigations are carried out at the outer race and its housing is modeled in three-dimension. Comparison has been made with an experimental vibration results with the simulated acceleration signal obtained from the dynamic model. The influence of housing structure with different height is investigated and corresponding vibration response has been evaluated using the root mean square parameter RMS. It was found that, the housing with less height has lowest fluctuation in the output response. Also, stability of bearing increased with the decrease of the bearing height, where the bearings with less height showed the best results.

A finite element contact bearing model [34] establishes a high-precision elastic based on a contact algorithm, in which all the important bearing geometry like internal clearance, roller and race crowning, race width and thickness, and dimensions of the raceway shoulders were included. This method is presented for calculating and analyzing the radially loaded double row bearing with a raceway defect of varying depth, length, and surface roughness [35], also validated by comparing experimental results to existing analytical models. The resonance frequency in the first vibration mode of mechanical system was studied [36]. According to this study, the envelope detection method for the first vibration mode resonance frequency could be effectively applied in the signal processing for the bearing defect diagnosis. It is also found that, the vibration signal amplitude for outer race defect is more than that of the inner race defect and the ball defect. The theoretical model was aimed to study the effect of defect size, load and speed on the bearing vibration and predict the spectral components.

To differentiate between vibrations signatures, Finite element model can be effectively used for defects of different sizes in the bearing [37]. Experimental measurement result has been taken for the analysis of the signal that has been obtained through the use of FFT analyzer. The vibration signal pattern obtained from the simulation was found to have similar characteristics with experimental data. A dynamic loading model simulates the distribution of load in the outer race due to transfer load from the ball. Time domain analysis is performed to evaluate the output result of vibration analysis from the finite element software. RMS and peak to peak value is used as the time signal descriptors and can be used as a parameter for condition monitoring purposes. The vibration response of healthy and defected bearing is compared with the simulated vibration pattern and observed similar characteristics obtained from experimental results, [38].

2. CONCLUSION

The SVD and ‘Hankel’ matrix based de-noising approach based fault-signature model and detection scheme, time - frequency analysis increases the possibility of inner-race defects identification easily, also it can identify rolling-element defects when the inner-race characteristic fault frequency, is an integer multiple of characteristic fault frequency due to rolling element. This fault-signature model and detection scheme can be further extended for rolling-element and cage defects. In the time–frequency manifold sparse reconstruction model studies the transient characteristics of signal from low signal-to-noise ratio (SNR). Among the various other methods, de-noising performance of TFM has a good result, since it combines the de-noising and atomic decomposition merits in image sparse reconstruction. This method is effectively verified by experimental analysis for bearing fault feature extraction.

A laboratory instructional module presented with conventional spectral analysis illustrated with a synthetic signal generated in MATLAB, also a graphically driven MATLAB software utility effectively explores the envelope analysis of measured data and the generated signal. Theoretical calculations were made to identify the characteristic frequencies of bearing under test. Also construction of synthetic signal using a square wave approximation, random noise, ringing pulse
sequence and their sum has been carried out and obtained spectra each sequence and is composite waveform. Using band pass filtering in “envelope analysis” and Hilbert transform for rectification rejects the low-frequency, high-amplitude harmonics, associated with imbalance and misalignment and to eliminate random noise outside the pass band to prevent loss of peaks in the composite signal. Spectrum analysis reported with GUI utilities in both MATLAB and LabVIEW implemented development programs confirms effective user friendly approach for fault diagnosis.

In very simple way the designer directly using auto computed FFT Power Spectrum virtual instruments program icon in LabVIEW of acquired vibration Signals and obtained the power spectrum, which clearly identifies fault in bearings, that too in static environment, not like all other reports uses only dynamic measurements technique.

The flexibility and efficient computational implementation in wavelets approach has proved to be a competent tool for bearing fault detection. Kurtosis coefficient in a time-domain statistics supports enhancing the de-noising effect further in the compound faults. The reliability and usage of this method are compared with other fault detection methods.

Excellent comparative study of faulty bearings were carried out successfully with current monitoring technique in bearing fault identification, and further confirmed that, the vibration signals technique is predominant than other methods for fault identification of the bearing elements.

Mathematical model approach provides high-precision elastic with a finite element contact bearing model and includes all the important bearing geometry like: internal clearance, roller and race crowning, race width and thickness, and dimensions of the raceway shoulders. Mathematical model also supports calculating and analyzing the radially loaded double row bearing with a raceway defect of varying depth, length, and surface roughness and validated successfully by comparing experimental results.

REFERENCES:


Recent Approaches and Measurement Techniques for the Bearing Fault Analysis – A Review


