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A Review paper on Vibration-Based Fault Diagnosis of Rolling Element Bearings

Vivek Kumar[1], Ganesh Pal Singh Jadon[2], Prem Prakash Pandit[3]
[1]*Research Scholar,* [2, 3]*Assistant Professor, Department of Mechanical Engineering, IPS College of Technology & Management, Gwalior (MP), India*

Abstract: One of the common crucial elements that decide the condition of machinery including its residual lifespan in the energy industry, automotive, hydroelectric dams, etc., is the rolling element bearing. Throughout the process, rigorous predictive condition monitoring tools like vibration control, and analysis are valuable methods that are demanded to ensure the safe condition of the rolling element bearings. The expected faults that offer ample cycle times for preventive management are suggested by a Predictive Health Forecasting instrument. Instead of simply identifying the faults, the Predictive bearing health Monitoring platform seeks to map the degradation, like wear progression. From the point of view of system condition control using vibration analysis, this article aims to summarize the fundamental science of rolling element bearings through these varied applications. Numerous vibration analysis approaches are employed to detect defects in REB. The aforementioned article explained different techniques for vibration analysis for REB defect investigation.
Keywords: Frequency domain, REB, Fault Investigation, Vibration Analysis, Fault Investigation.

I. INTRODUCTION

In industrial machinery, rolling element bearings (REBs) are often employed and are viewed because of the common important element. In power plants, industrial plants, transportation sectors, and even industrial equipment, the appropriate operation of bearings is quite essential. The Electric Power Research Institute (EPRI) performed a broad research study on electric engine defects in 1985 and reported around 41% of defects were consistent with damaged motor bearings [1]. The healthy and stable operation of rolling element bearings in industrial machinery depends upon the kind of bearing selected and also unique precision including all relevant parts, such as a shaft, housing, belt drive, gear, nuts, etc. [2]. Robust Predictive Health Monitoring (PHM) methods remain essential in assuring the safe condition of REBs throughout the process. That PHM method shows significant potential faults and offers additional freedom for the routine maintenance task. The PHM method attempts to track the degradation. The wear progresses instead of only identifying the faults.

There are a variety of research papers that are relevant to the health monitoring of REB [2–8]. This article illustrates quite well the established signal processing (SP), diagnostic, and prognosis research approaches including their difficulties, improvements, moreover weaknesses. Several trials also examinations were carried to examine the existence of bearing faults with the aid of multiple analysis methods these are friction, oil-debris, Shock-Pulse Measurements (SPM), etc. The signal processing methods have been implemented to prepare the signals such as root mean square (RMS), kurtosis, Fast Fourier Transform (FFT), etc. Nevertheless, numerous difficulties need extra ahead SP systems, for example, to eliminate the noise from signal also the speed variation result.

A comprehensive investigation on vibration strategies for classification of fault in REBs offered by Tandon and Nakra [9]; they deliberated vibration measures in the time domain also in the frequency domain, sound analysis, shock wave system in this study. Tandon and Choudhury [10] conducted a study on vibration techniques toward these identification faults in REB; the review starts by introducing the basics of rolling bearing and their modeling methods.

Next, the tracking procedures, signal processing, testing approaches, and condition prediction for REB are checked. Eventually, all these topics are objectively addressed to draw some of the implications of recent findings, evolving patterns, and the fields whereby further study and investigation is required.

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II. APPROACHES TO BEARING DEFECT

REB is a mechanical part that holds loads. All rolling bearings, as seen in Fig. 1, have four main elements: an inner race (IR), an outer race (OR),ball or roller, and a cage.

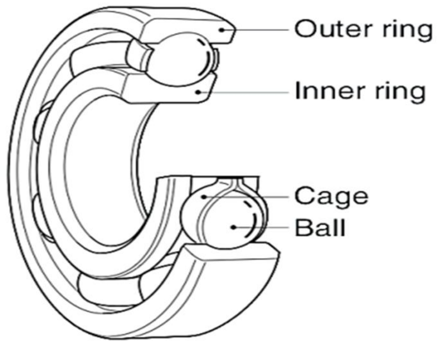

Fig 1.Rolling element bearing four basic element.

The fundamental cause for bearing defects in the surface contact stresses that may change increasing working loads, excess stresses because of defect presence these are imbalance, misalignment, bent shaft, looseness etc. Throughout the times, multiple dynamic methodologies have become introduced to analyze the changing behavior and characteristics of REB. The dynamic models of REB were obtained first by Palmgren and Harris [11][12]. The greatest share of the research has concentrated on the localized defects employing various modeling methods. McFadden and Smith [13], McFadden and Smith [14], Tandon and Choudhury [15], and Sawalha and Randall [16] insert the artificial fault as a signal feature of the impulsive train in the modeled device.
Inappropriate construction of the REB or incorrect processing, misalignment of the shaft, the odd diameter of REB, irregular oiling, overstressed, fatigue, irregular wear, and other factors may cause defects in REB. REB having two variety of fault present these are dispersed and clustered faults. Fig 2 represents the various investigation approaches of bearing diagnosis using vibration analysis.

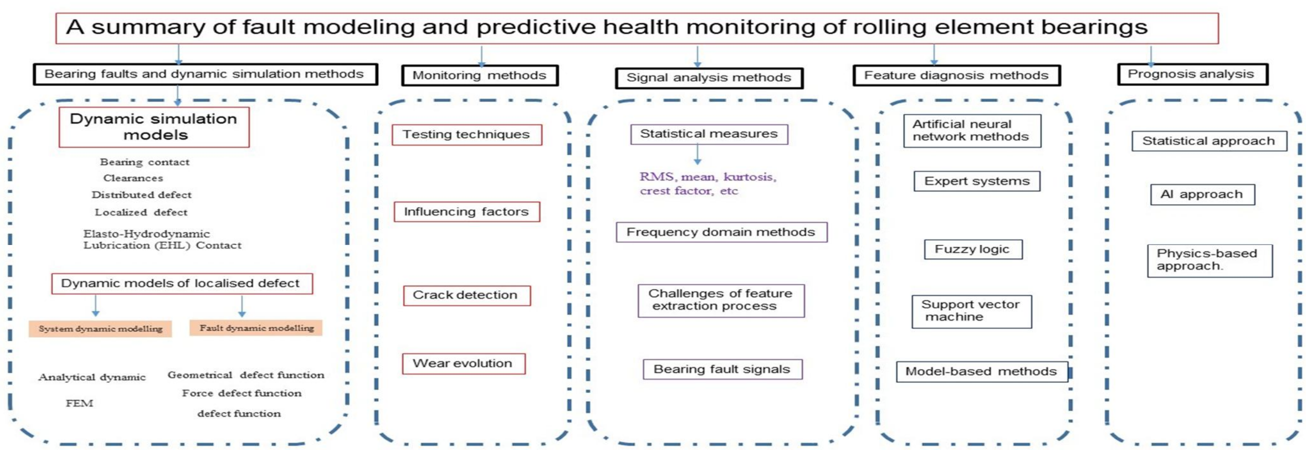

Fig 2.A review of rolling component bearing fault modelling and predictive health monitoring.

A. *Distributed Defects*

Manufacturing faults, incorrect assembly or installation, and wear are some most frequent events of distributed defects [17]. Surface roughness, waviness, misaligned races, and disproportionate diameter of rolling components are cases of spread defects [18][19]. The vibration frequency increases as the interaction force between bearing components and raceways vary due to scattered defects. As a consequence, the analysis of vibrations induced through transmitted defects is predominantly used during bearing quality inspection [20].

B. Localized Defects

Fatigue-induced defects on rolling surfaces include cracks, holes, and spalls [8]. The fracture of the races or rolling components is a typical failure mechanism that occurs when a fatigue crack begins under the bearing and develops until a some bearing metal particle is removed, resulting in a minor defect [9]. Since the bearing is overwhelmed or exposed to dynamic loads during working, this defect accelerates, and it also increases with rotational speed. The inner race (IR), outer race (OR), and ball or roller are all susceptible to spalling.

III. FREQUENCIES OF BEARING CHARACTERISTICS

As a system with a REB runs at a definite velocity, a fault progresses, and the vibration spectrum of the REB varies. Bearing fault frequencies or bearing feature frequencies are the frequency frequencies of shocks induced by faults in bearings. A bearing characteristic frequency is assigned to each bearing element. Lead to an increase in vibrational energy, peaks will occur at these frequencies. On REB, the onset and development of defects or faults create distinct and consistent vibration characteristics. Tandon and Choudhury [23], [24] proposed a model that projected a frequency range with peaks at these frequencies. A particular defect is caused by faults in REB components such as the IR, OR, Ball, and cage. Frequency is a concept that refers to the number of times
Following assumption used in bearing equation, only rolling, and the ball rolling over the raceway surface. But, this is not valid due to the various factor of rolling elements undergoes a series of sliding and rolling

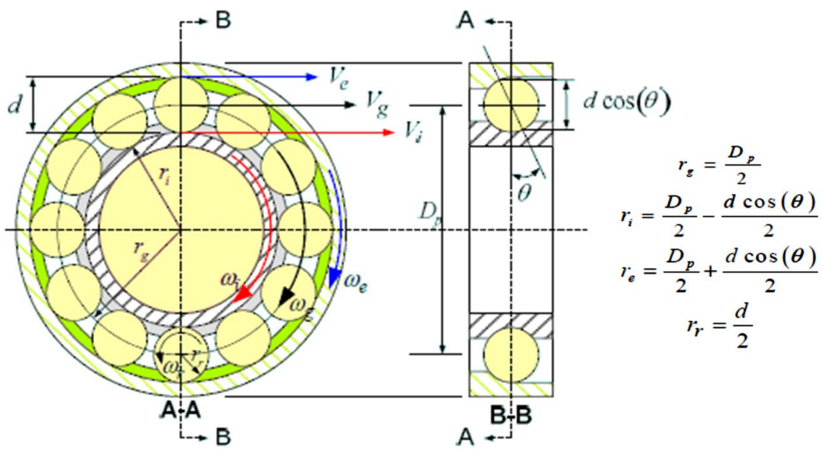

Fig 3. Rolling element bearing geometry

Defected bearing generates fault frequencies reliant on geometry of REB, N= number of rolling elements and ω=shaft angular speed. Fig 3 and Table1 represents the various frequency and geometry element of REB.

TABLE 1.NOTATION

S.No	Terms	Rolling Element	Cage	Outer Race	Inner Race
1	Angular Velocity	ω_r	ω_g	ω_o	ω_i
2.	Linear Velocity	V_r	V_g	V_o	V_i
3.	Radius	r_r	r_g	r_o	r_i
4.	Rotation Frequency	f_r	f_g	f_o	f_i
5.	Diameter of Rolling Element		d		
6.	Diameter	--	--	D_o	D_i
7.	Pitch		P		
8.	Contact Angle		θ		
9.	Number of Rolling Element		N		

The mathematical equation can be simplified are as follows,

$$FTF = f_g = \frac{1}{2}\left[f_i\left(1 - \frac{d\cos\theta}{D_p}\right)\right] \quad (1)$$

$$BPFO = \left\{\frac{N}{2}\left[f_i\left(1 - \frac{d\cos\theta}{D_p}\right)\right]\right\} \quad (2)$$

$$BPFI = \left\{\frac{N}{2}\left[f_i\left(1 + \frac{d\cos\theta}{D_p}\right)\right]\right\} \quad (3)$$

$$BSF = f_r = \frac{D_p}{2d}(f_i)\left[1 - \left(\frac{d\cos\theta}{D_p}\right)^2\right] \quad (4)$$

From equation (14), (15), (16) and (17), the following relation is obtained

$$\text{BPFI} = \text{N}\ (FTF) \quad (5)$$

$$\text{BPFI} = \text{N}\ (f_i - FTF) \quad (6)$$

IV. TECHNIQUES FOR VIBRATION ANALYSIS

The bearing vibration is analyzed using a diversity of vibration measurement procedures. Vibration analysis methods are grouped into four groups in this paper: time domain, frequency domain, and time frequency-domain analysis.

A. *Time domain techniques*

Because of the association of local imperfections with the REB components, the vibration energy of the bearing data varies. The time-domain vibration signal captured from the faulty bearing shows a transition in vibration energy in the arrangement of peaks. Where there are several faults on the races, the ball or roller of bearing hit the fault after a certain amount of time has passed, resulting in peaks (impulses). The time interval among two successive impulses is determined by the angular orientation of the defects on the runs, as well as the amount of single defect ball transfers.

Time domain analysis examines the signal as a function of time. In time domain statistical feature is determined for REB vibration data. In the contrary, this technique has inadequate diagnostic abilities, bearing defect may be classified but it may not make a straightforward statement of where the bearing defect is; e.g. REB damage, unbalance, and misalignment. Time domain is useful for trending analysis. When it comes to time domain analysis following equation that is sensitive to impulsive oscillation, these are

(1) R.M.S. – is the square root of the arithmetic mean of the square of the value

$$RMS_x = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N}(x_i)^2\right]} \quad (7)$$

Where *x* represents original sampled signal data, *N* represents the number of samples and *I* represents the sample index.

(2) Kurtosis – is a degree of the tailedness of a real-valued random variable's probability distribution, as well as the number of peaks in the waveform.

$$K = \frac{N\sum_{i=1}^{N}(x_i - \bar{x})^4}{\left(\sum_{i=1}^{N}(x_i - \bar{x})^2\right)^2} \quad (8)$$

(3) Crest Factor – may indicate developing fault whereas RMS level (High Energy Level) may indicate the severe defect.

$$CF = \frac{PeakValue}{RMS} \quad (9)$$

(4) Mean Value – The mean values of a time domain signal indicates the central tendency of the vibration data.

$$\text{Mean} = \mu_x = \frac{1}{N}\left[\sum_{i=1}^{N}(x_i)^2\right] \quad (10)$$

(5) Peak value – It highlights the highest value of vibration data. With the support of peak value, the time instances of maximum amplitude can be evaluated. It is calculated as:

$$x_{Pk} = \max(x_i) \quad (11)$$

(6) Skewness – It is the third order moment about its mean. This property explains how the signal is symmetrical in relation to its mean value.

$$skewness = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{x_i-\mu}{\sigma}\right]^2 \quad (12)$$

(7) Variance- The spectrum of numbers in a data set is determined by variance. The variance measures the difference between each number in the set and the mean.

$$\sigma^2 = \mathrm{var} = \frac{\sum_{i=1}^{N}(x_i-\mu)^2}{N} \quad (13)$$

(8) Standard deviation-is a measure of spread.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i-\mu)^2}{N}} \quad (14)$$

Figure 4 shows the original inner race fault signature sample data in the time domain.

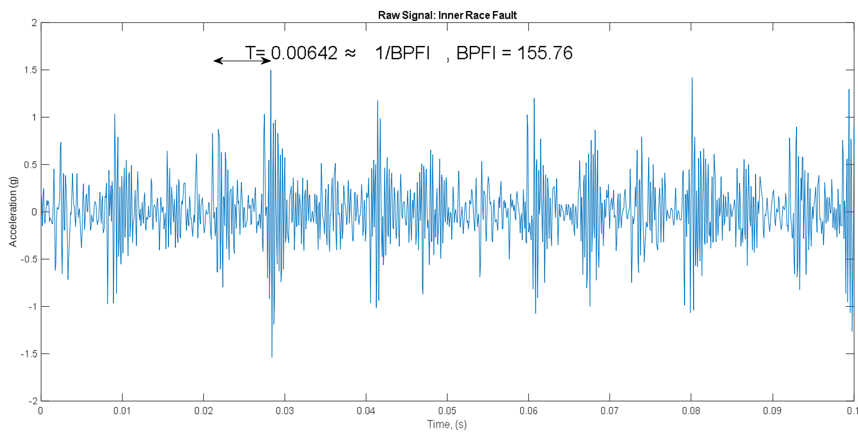

Fig. 4. Time-domain raw signal from inner race fault.

The original signal amplitude is modulated at a certain frequency, the time-domain signal, as well as the Time period, demonstrate this. $T = 0.00642 \approx 1/BPFI$, $BPFI = 155.76$ shown in Fig. 4. It means that the inner race of the REB has a fault.

B. Frequency Domain Analysis.

The most general practice for diagnosing bearing faults is frequency domain technique. In this technique time-domain vibration data converted into discrete frequency components by means of a fast Fourier transform (FFT). J.W.Cooley and J.W.Tuckey [25] first published the FFT practice for calculating the discrete Fourier Transform (DFT). The frequency axis is on the X-axis, and the amplitude of displacement, velocity, or acceleration is on the Y-axis in a frequency spectrum graph. The main benefit of this technique is the capability to discover particular frequency components of interest. The series of peaks appearing and vanishing in the continuum was well described by James Taylor [26]. The identification of the position of a defect in a rolling part bearing necessitates a comprehensive understanding of bearing characteristics frequencies. By comparing the signature defect frequencies to the main frequency constituents present in the continuum, the power spectrum may be used to locate rolling part defects. The inverse Fourier transform of the logarithmic power spectrum is known as the power cepstrum, which is an effective bearing fault detection technique. Merwe and Hoffman [27] suggested an updated cepstrum analysis.

Another common technique for spotting the incipient failure of REB is enveloping amplitude demodulation. High-frequency resonance approach [27][29], amplitude demodulation [19], demodulated resonance study, and narrowband envelope investigation [30][31] are some of the other names for this process. Envelope analysis, also known as amplitude demodulation, is a technique for removing periodic impacts from modulated random noise created by a defected REB. This method is also probable once the signal from the REB is reasonably truncated in energy and "submerged" with the additional vibrations formed by the device. Consider a fault on REB that creates a very short impulse or impact as the rolling part or another surface in the bearing rolls over it. Since the energy of this effect is transmitted at a low frequency over a large frequency range, identifying a bearing defect in the vicinity of vibration from multiple device components using the normal spectrum is difficult. The effect excites the REB's natural frequency, resulting in a much higher frequency of vibration energy than vibrations emitted by other device components. Periodic impacts appear as a peak (with several harmonics) in the envelope spectrum following the damaged bearing element at the fault frequency. Enveloping clearly described REB fault characteristic method. Several researchers have assessed the efficacy of this approach. In envelope analysis, the Hilbert transform is a useful method. It's also been used to track and diagnose system faults [32] [33]. Ho and Randall [33] showed that using a self-adaptive Noise Cancellation technique in combination through an envelope detection system yields better results.

C. Time-Frequency Domain

The ability to accommodate mutually stationary and non-stationary signals is the greatest advantage of time-domain techniques over frequency-domain techniques. Time–frequency analysis, which typically confers their time-variant characteristics, may be used to see the signal frequency components. Some of the time-frequency investigation used are the Short-Time Fourier Transform (STFT), Wigner-Ville Distribution (WVD), and Wavelet Transform (WT). The STFT approach is used to diagnose bearing defects in rolling elements [36].The basic principle behind the STFT is to divide the original signal into small fragments with a limited time window, then use the Fourier transform to evaluate the frequencies present in each fragment. The wavelet transform (WT) has the advantage of being able to reach higher frequency resolutions with sharper time resolutions than the STFT. Wang et al. [37] developed an advanced Kurtogram system for diagnosing rolling part bearing faults. In this Kurtogram process, the kurtosis of transient signals purified by the STFT is used. A Wigner-Ville distribution is a typical time-frequency analysis. And it is not influenced by time localization or frequency resolution interference because it does not use a window feature.

The most commonly used tool for diagnosing bearing faults is the wavelet transform (WT) [38] [39]. Rubini and Meneghetti [40] adopted the average wavelet frequencies on a preferred band that is not affected by system resonance. Dalpiaz and Rivola [41] compared the wavelet transform operation's simplicity and efficiency to further vibration investigative approaches.Mori et al. [42] projected the spalling on the REB by put on discrete wavelet transform (DWT) to signals. Prabhakar et al. [43] found that the DWT is an appropriate technique for distinguishing individual and various defects in REB.Wang and Gao [44] suggested using the wavelet transform after the Fourier transforms to boost feature extraction. Sun and Tang [45] used a continuous wavelet transform singularity investigation to detect REB flaws.Jing and Qu [46] created a Morlet wavelet-based denoising method for feature extraction, which they used to classify REB's IR fault. For vibration monitoring, several researchers [47][48] investigated an pioneering transform identified as the wavelet packet transform. Yunlong and Zhenxiang [41] suggested a system for diagnosing rolling bearing faults that merged kurtosis and wavelet analysis. This system will identify bearing faults that have been observed by experiments easily and effectively.

V. CONCLUSION

A summary of recent findings and advances in vibration analysis methods for diagnosing rolling part bearing faults is presented in this article. This research discovered that time-domain techniques can only show the occurrence of faults in the bearing, but not their location. Frequency domain techniques can pinpoint the direction of a bearing's fault(s). Vibration peaks appear in the spectrum at characteristic frequencies, allowing one to determine which bearing part is defective.

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