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Investigation for Distributed defects in Ball bearing using Vibration Signature Analysis- A Review

Engineering

KEYWORDS : Ball bearing, distributed defects, vibration analysis, wavelet transform

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ABSTRACT

Rolling element bearings are extensively used in most of rotating machinery. For its precise & efficient performance it is necessary to monitor the condition of rolling element bearing to avoid catastrophic failure of machinery. This paper presents the review of Vibration signature analysis of ball bearing with distributed defects on surfaces of inner & outer races. Distributed defects include surface roughness, waviness, off size rolling element & misaligned races. These are caused due to manufacturing error & operating conditions. The main objective of this review is to investigate the effect of distributed defects in ball bearing on vibration signature. The effect produced by local defects in stationary condition becomes more severe in non-stationary condition & spreads to form distributed defects. Traditional techniques of vibration signature analysis are available for the detection of bearing fault. But when signals are complex & non stationary, these techniques have limitation to diagnose faulty signal. Wavelet Transform is time frequency analysis method gives better performance for analyzing non- stationary signal various parameters like defect type, defect location & defect size for variable speed & load condition is reviewed.

INTRODUCTION:

Rolling element bearing find widespread domestic & industrial applications proper functioning of these appliances depends, to great extent, on the smooth & quiet running of bearings. In industrial applications, bearings are considered as critical, unless detected in time, causes malfunction & may even lead to catastrophic failure of machinery.

Bearing defects may be categorized as localized & distributed. The localized defects include cracks, pits & spalls caused by fatigue on rolling surface. The distributed defect includes surface roughness, waviness, and misaligned races & off size ball. Hence detection of these defects is important for quality inspection of the bearings.[21]

There are different methods for detection & diagnosis of bearing defects, such as vibration & acoustic measurement, temperature measurement, wear debris analysis. Several techniques have been applied to measure vibration responses from defective bearings such as time domain, frequency domain, shock pulse method, sound & intensity techniques, acoustic emission.[5]

Complex & non-stationary vibration signals with large amount of noise make fault detection challenging in case of rolling element bearing. Wavelet transform has local characteristics of time domain as well as frequency domain & changeable time frequency window which gives better performance for analyzing non-stationary signals.[13]

When defect occurs on the surface of bearing elements, series of impact are generated every time, when rolling element interact with defect, which results excitation of bearing system. This causes a significant increase in vibration level. The variation in contact force between rolling element & raceways due to distributed defects results in increase in vibration level. Even when local defect grows, it becomes distributed one. In such case no sharp pulses are generated but it gives more complex signal with strong non-stationary components.

2. BEARING FAILURE:

The review shows influence of modes of failure on bearing dynamics & resulting forces. [21,5].

2.1.1 Fatigue: A bearing subjected to normal loading will fail due to material fatigue such as pitting, spalling, after a certain running time. Fatigue damage begins with the formation of minute cracks below the bearing surface [3,4]. As loading continues, the cracks progress to the surface where they cause material to break. The surface damage severely disturbs the motion of the rolling elements which leads to the generation of short time impacts repeated at rolling element defect frequency.[21, 16, 14].

2.1.2 Wear: Wear is common cause of bearing failure, caused mainly by dirt & foreign particles entering the bearing through inadequate lubrication. Severe wear changes the raceway profile & alters the rolling element profile, increasing the bearing clearance. Increase in rolling friction leads to high levels of slip & skidding, results in complete breakdown [3].

2.1.3Plastic Deformation: This failure occur when bearing subjected to excessive loading while stationary or undergoing small movements. In operation, the deformed bearing would rotate more unevenly producing excessive vibration.

2.1.4 Corrosion: Corrosion damage occurs when water, acids or other contaminants in the oil enter the bearing arrangement. This can be caused by damaged seals, acidic lubricants or condensation. As the rust particles interfere with the lubrication rust on the running surfaces produces uneven & noisy operation.

2.1.5 Brinelling: Brinelling is regularly spaced indentations distributed over the entire raceway circumference in the Hertzian contact area. Three possible causes of brinelling are (1) static overloading which leads to plastic deformation of the raceways, (2) vibration & shock loads (3) when a bearing forms the loop for the passage of electric current. This results in repetitive indentations of the raceways. The bearing operation will be noisy & uneven in presence of small fatigue producing sharp impacts with the passage of the rolling elements.

2.1.6 Lubrication: Inadequate lubrication is one of the common causes of premature bearing failure as it leads to skidding, slip, increased friction, heat generation. At the highly stressed region of Hertzian contact, when there is insufficient lubricant, the contacting surfaces will weld together [7]. Improper lubricant selection reduces hardness & fatigue life.

2.1.7 Faulty Installation: Faulty installation can include effects as excessive preloading in either radial or axial directions. Misalignment, loose fits or damage occur due to excessive force used in mounting of bearing components. Such misalignment generates a uniformly wide wear track at the rotating raceway extending over the entire circumference.

2.1.8 Incorrect Design: Incorrect design can involve poor choice of bearing type or size for the required operation. Incorrect bearing selection can result in low load carrying capability The end result will be reduced fatigue life. [7]

3.VIBRATION GENERATIONS IN ROLLING ELEMENT BEARING

3.1 Geometrical Imperfection:

a. **Waviness:** These are global shaped sinusoidal shaped imperfections on outer race of bearing components. Waviness causes the variation in contact loads when bearing is running. The magnitude of variation depends on amplitude of imperfection & stiffness of contact. Due to this variation in contact loads, vibrations are generated in bearing.
b. **Excitation Frequency**: The rotational speed of inner ring, outer ring & rolling element is usually different. Because of waviness in all these bearing elements, vibration is generated at distinct frequency. The excitation frequency is proportional to rotational speed of the shaft. The ratio of these two frequencies is excitation order.

Table 1 shows the excitation frequency of different vibration sources in a ball bearing [8]

Vibration Source	Wave-number	Frequency
Parametric excitation	---	q*z*Wc
Inner ring waviness	N=q*z+/-k	q*z*(Wir-Wc)+/-k*Wir
Outer ring waviness	N=q*z+/-k	q*z*Wc
Ball waviness	N=2q	2*q*Wre+/-k*Wc
Ball diameter variations	---	k*Wc
Cage run out	---	q*z*Wc+/-k*Wc

Wir,Wc,Wre denoted the angular speed of inner ring, cage & rolling element respectively. Where z=total number of rolling elements & k= Vibration modes of inner & outer ring of bearing, q refers to harmonics of ball pass frequency.

3.2 Parametric Excitation: In rolling element bearing vibrations are caused by rotation of finite number of loaded rolling contacts between rolling elements & guided rings. Bearing stiffness becomes explicitly dependent on time. This time varying stiffness causes the vibrations, even in absence of external load. As contact behavior is nonlinear, the effect of an asymmetric stiffness distribution in application where bearing is subjected to external radial load.

4.BEARING FAULT DETECTION TECHNIQUES: There are several techniques that can be employed to predict the condition of bearing, such as vibration monitoring, Current Signature Analysis, Tribology, Thermography etc. The most important technique in predictive maintenance is vibration analysis as it gives clear indications regarding the condition of the machine, in addition the level of vibrations & the frequency at which these vibrations occur. It can also show the exact location of the defect & possibly severity of such defect.

Tab.2 Comparison of various methods of fault detection [1]

Fault	Measurement Methods					
	Temp.	Pressure	Flow	Oil Ana.	SPM	FFT
Bearing Damage	*			*	*	*
Cracking						*
Bent shaft						*
Looseness						*
Rubbing					*	*
Noise						*
Leak		*			*	
Unbalance	*					*
Misalign	*					*
Journal Bearing	*	*	*	*		*
Gear damage				*		*

5. Vibration MEASUREMENT:

A number of transducer exists for measuring machine vibration, including proximity probe, velocity transducers, accelerometers etc. The measurement of machine casing acceleration is the most common method used for bearing fault detection. Piezoelectric accelerometer placed externally on the machine casing, on the bearing housing. Piezoelectric sensors are less sensitive to temperature which is important since most machinery fault results in temperature increase [21]. This will allow the bearing vibration to transmit readily through the structure to transducer. Accelerometers have the advantage of providing a wide dynamic & frequency range for vibration measurement.

Velocity transducers are used for measuring the velocity of the machine casing to which they are attached. They have not found wide acceptance for bearing fault detection. But there is wider frequency range available with accelerometers found to be better, even for slow speed rotating machinery. Proximity probes are also used for bearing fault detection by mounting directly on the outer race to measure outer race deflection at each ball pass.

6.VIBRATION SIGNATURE ANALYSIS

6.1 Time Domain Technique:

Signal analysis in time domain is used to monitor the condition of machine. Some of time domain technique measure vibration signal by number of statistical parameters such as RMS peak, Crest factor, Kurtosis, clearance factor impulse factor, shape factor & beta moments.

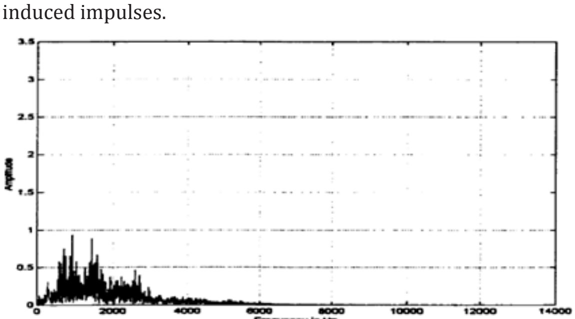
1. Root mean Square
2. Mean:-
3. Peak value:
4. Crest Factor
5. Probability Density function: The probability density of signal can be estimated by determining the time duration for which signal remains in a set of amplitude windows.
6. Kurtosis: The statistical index Kurtosis represents a good indicator for the analysis of damages in low speed machinery with no continuous shocks. It describes the impulsive shape of time signal. Two approaches may be used for time domain statistics. A signal with Gaussian distribution for acceleration whose kurtosis is 3, while in presence of impulsive signal whose distribution of data is non Gaussian havening kurtosis value greater than 3.

6.2.Frequency Domain Technique: It is common to refer power spectrum when analyzing vibration data in frequency domain. The discrete time signal x(t) represents a sampled periodic function with period T, The Fourier series expansion of x(t) can be obtained by Fourier integral

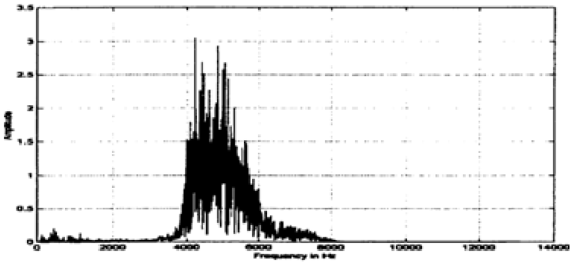
Where f represents the discrete equally spaced frequencies being multiples of reciprocal of the period T. The power spectrum P(f) is magnitude obtained from Fourier integral can be estimated as

Where * represents complex conjugation & E[ ] represents the expected value.

Normally, diagnosis of Bearing defects & detecting the presence of periodical components in a signal has done by analyzing the spectrum of the signal. Figure 5(a) show the frequency spectra of the vibration signals as shown in Figure5 (b), Distinctive peaks can be observed in the frequency spectrum of the defective bearing compared to that of the good bearing due to defect-induced impulses.



Fig(5) (a) Frequency Spectra of Vibration signal with Bearing in good condition



Fig(5) (b) Frequency Spectra of Vibration signal with Bearing in defect condition

Contact stresses at the interface between the rollers & the raceways are relatively high. Abrupt changes in the stress caused by the passage of defects results in impulsive excitations to the structure. This impulsive force may excite resonance in the bearing & the housing structure. The excitation decays quickly due to damping of the structure. Passage on the fatigue spall produces a series of damped oscillations with the time intervals between the two consecutive peaks corresponds to the time between the passings of the fatigue spall.

6.3 Envelope Analysis:
Envelope analysis [17] is concept that each time localized defect in bearing make contact under load with another surface in the bearing, an impulse of vibration is generated. This impulse will have an extremely short duration compared to interval between impulses & so its energy will be distributed across a very wide frequency range. The result is that various resonances of bearing & the surrounding structure will be excited by the impacts. The excitation is normally repetitive because a contact between the defect & mating surfaces in the bearing is essentially periodic.

The frequency of occurrence of the impulses is referred to as the characteristic bearing defect frequencies. It is usual to consider the resonance as being amplitude modulated at the characteristic defect frequency which makes it possible not only to detect the presence of defect by excitation of resonance but also to diagnose component of the bearing.

An approximation which is useful for investigating effects of enveloping is to replace rectification by squaring operation & smoothening the circuit by low pass filter,

$$x(t)^2 = \sum_{i=1}^{N}\sum_{j=1}^{M}\frac{1}{2}ai\ \ aj\ \left[cos\big((\omega i+\omega j)t + \varphi i+\varphi j\big) + cos\big((\omega i-\omega j)t+\varphi i - \varphi j\big)\right]$$

It is seen from equation that the squaring operation creates sum & differences in frequencies from original frequency components with sum frequencies represented by & difference frequencies terms. After squaring the signal is low pass filtered to remove the sum terms & leave the difference terms, analogues to smoothening operation. The final envelope signal is given by

$$y(t) = \sum_{i=1}^{N}\sum_{j=1}^{M} ai\ \ aj\ \ cos\big((\omega i - \omega j)t + \varphi i - \varphi j\big)$$

It is noted that the original vibration signal may have at relatively high frequency; the resulting envelope signal only contains low frequency information.

6.4 Cepstrum Analysis : Cepstrum analysis was originally proposed by Bogert for processing seismological data for separating out the influence of echoes from data. The Cepstrum was originally defined as "power spectrum of logarithmic power spectrum" but a number of variations have also been developed. The general definition is

$$C(\tau) = F^{-1}\{\log F(x(t))\}$$

Where the originally frequency spectrum F(x(t)) can be either a power spectrum or a complex spectrum.

6.5 Time Frequency Analysis: Time frequency techniques show potential for detecting bearing problems in some of the more complex classes of rotating machines where the signal to noise ratio is low & a large number of frequency components are present. Non stationary signals can be analyzed by applying time frequency domain techniques. Wavelet analysis is windowing technique with variable sized regions. It allows the use of long time intervals for more precise low frequency information & shorter regions for high frequency information.

7. RECENT TECHNIQUES:
R.Randall,et.al[22] presented review of diagnostics analysis of acceleration signal from REB used for very low & high speed application. Signal analysis techniques are described to identify impulsivity nature of signal in case of impact.

N.K.Nikolauo[12] proposed vibration analysis of rolling element bearing with local defect by using wavelet packet transform. Wavelet packet decomposition tree is implemented in three levels for fine components of signal. A code of algorithm is developed under Lab-View programming & experimental measurements are conducted on Lab. machinery fault simulator.

Kun Feng et.al.[9] have proposed differential evolution optimization & anti-symmetric real Laplace wavelet filter based methods are used to extract noisy vibration signal of faulty rolling element bearing. The resonance of impulse signal is obtained by impulse response function using transient vibration.

Zhongquing[34] has presented work to extract fault features of vibration signal by envelope demodulation technique based on wavelet transform & energy operator. Proposed technique not only avoids artificial carrier signal with b& pass filtering but give excellent performance in constraining noise.

Ruqiang Yan et.al. [23] has proposed Non-stationary Signal analysis, done for machine health monitoring based on Hilbert Huang Transform. Empirical mode decomposition process is used for extracting features. He concluded as defect size increases, different intrinsic modes excited result in change of frequency in transient vibration

Wei Guo, et.al.[29] have proposed method based on ensemble empirical model decomposition which decomposes the vibration signal into intrinsic mode functions Proposed method extract important impulses related to bearing faults & reduces size of vibration data as well as noise. He suggested that increasing ensemble numbers helpful for reducing remaining noise in each IMF.

Y. Liu [33] has proposed an adaptive algorithm based on stationary wavelet packet decomposition & Hilbert transform, proposed to extract bearing fault characteristic from vibration signal. Algorithm only extracts wavelet decomposition parameters containing bearing fault frequency

Wen-chang et.al.[30] have proposed to characterize the feature extraction of vibration signals of faulty bearing, envelope analysis is used along with empirical mode decomposition. Proposed method is compared with traditional envelope analysis.

8. VIBRATION RESPONSE DUE TO DISTRIBUTED DEFECTS IN BEARING:
Two approaches have been adopted by researchers for creat-

ing distributed defects on bearings to study their vibration response. One is to run bearing until failure & monitor the changes in the vibration response & other approach is to artificially introduce the defects in bearing by acid etching, spark erosion & electro-discharge machining & measure the vibration response.

Meyer,et.al.[10] developed a analytical model for ball bearing vibrations to predict vibration response to distributed defects. The operating modes for family of distributed defects on bearing shows, magnitude of contact force varies continuously & periodically as bearing rotates.

Sunnersjo [3] studied the vibration characteristics of the bearings having inner race waviness & varying ball diameter & found that significant peaks occur at the cage speed for a non uniform ball diameter.

Ian Howard [7] addressed science of bearing vibration, bearing kinematics & dynamics, vibration measurement, signal processing techniques & prognosis of bearing failure. He includes the review of various vibration signal processing

P.Mcfadden,et.al.[18] has developed the model for high frequency vibration produced by multiple point defects on inner race of REB under radial load. He showed that the frequencies of components from the defects are independent of position but the phase angle of these components is related to position of defect & frequency of components.

N.Tondon et.al.[27] prepared theoretical model to predict the vibration response of bearing to distributed defects under radial load. He considered the distributed defects such as waviness of outer, inner race & off size rolling element. This model predicts the amplitude of spectral components due to outer race waviness is much higher as compared to those due to inner race waviness.

Zeki Kiral et.al.[35] presented a method based on finite element vibration analysis for defect detection in rolling element bearing with single & multiple defects on different components of bearing structure using time & frequency domain parameters. Wear & geometric form errors of the raceways can also give rise to periodic vibrations. Analysis gives more complex signal with strong non-stationary components due to change in fault signature.

Yhl [32] proposed a linear model for the vibrations of the shaft bearing system caused by ball bearing geometric imperfections. These imperfections covered are radial & axial waviness of outer & inner rings, ball waviness, & ball diameter oversize.

Aktürk [2] simulated the effect of bearings surface waviness on the vibration by a computer program. The results are obtained in both time domain & frequency domains.

9. CONCLUSION

This paper has attempted to review fundamentals & practical applications of the vibration signature analysis used for bearing fault detection. These include the time domain statistics, frequency domain parameters, envelope & Cepstrum analysis. The majority of these parameters will require detailed knowledge of the bearing defect frequency to correctly diagnose bearing failure. Time frequency analysis is more popular to investigate transient features such as impact exciting resonances. Localized fatigue damage of the bearing raceways & rolling elements will be easiest failure mode to detect because the characteristic bearing defect frequencies are well understood. Wear & geometric form errors of the raceways can also give rise to periodic vibrations.

From above review it is seen that most of researchers focused their attention on the detection of localized defects in the bearing whereas less attention is given to distributed defects. In such cases, classical techniques are not more effective to recognize the presence of fault and characteristic frequency. However when local defect grows, it becomes distributed one. In this case no sharp pulses are generated but it gives more complex signal with strong non-stationary components due to change in fault signature. There is necessity to access effective tool and technique for diagnostics of distributed faults in ball bearing.

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