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Research Article

A Review on Investigation of Effect of Surface Defect on Ball Bearing Vibration Response

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Abstract

Rolling element bearing faults are among the main causes of breakdown in rotating machines. The influence of surface defects on contact behaviour is of great importance in many tribological situations. This paper presents the review of Vibration response of ball bearing with surface defect on the races of ball bearing. The effect of different types of defects affect the bearing performance but the most common type is the surface defects on the races which may cause sudden failure of machine and hence rated life reduces. Surface defects include surface roughness, waviness & misaligned races. These are caused due to manufacturing error & operating conditions. Bearing failures contribute major cause of machinery breakdown resulting in costly downtime. To prevent such failure bearing condition monitoring methods have been developed The study of vibration response due to surface defect is necessary for condition monitoring of rolling element bearing to improve bearing performance.

Keywords: *Ball Bearing, Surface Defect, Vibration Analysis.*

1. Introduction

Rolling element bearings are widely used in industry from home appliances to helicopter gear boxes. Proper functioning of these machine elements is extremely important in industry in order to prevent long term, costly catastrophic downtimes. Rolling element bearings are manufactured by assembling different components: the outer ring, the inner ring and the rolling elements which are in contact under heavy dynamic loads and relatively high speeds. The Hertzian contact stresses between the rolling elements and the rings are one of the basic mechanism that directly related with the operational conditions and initiates a defect (Zeki Kiral, 2002). Also the radially loaded rolling element bearings generate vibration even if they are geometrically perfect. This is because of the use of a finite number of rolling elements to carry the load. The number of rolling elements and their position in the load zone change with bearing rotation, giving rise to a periodical variation of the total stiffness of the bearing assembly.

The defects in rolling element bearings can be classified into three broad categories as localized defects, extended defects, and distributed defects. The localized defects include cracks, pits & spalls caused by fatigue on rolling surface. The distributed defects in rolling element bearings include surface roughness, waviness, misaligned races, and off-size rolling elements. The surface features are considered in terms of wavelength compared to Hertzian contact width of the rolling element raceway contacts. Surface features of wavelength of the order of the contact width or less are termed “roughness” whereas longer wavelength features are termed “waviness”.

An extended defect can be characterized as a defect that is larger than a localized defect (for example, its size can be greater than the spacing between two rolling elements), but smaller than a distributed defect (for example, waviness is generally along full raceways). Once a localized defect (a spall) is created on either raceway of a bearing due to surface fatigue, the continuous and repetitive passage of the rolling elements over the spall results in the generation of impulsive (contact) forces during the re–stressing of the rolling elements. This cyclic operation wears the edges, especially the trailing edge, of the spall causing it to gradually grow or expand in size, and results in the generation of an extended defect. (Sarabjeet Singh *et al*., 2015).

The distributed defects are caused due to manufacturing error, faulty installation, abrasive wear, poor maintenance. The variation in contact force between rolling elements and raceways due to the distributed defects results in increased 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. The study of vibration response due to this category of defect is, therefore, important for

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quality inspection as well as condition monitoring. (N. Tandon *et al*., 2000)

The vibration analysis of the rolling element bearings is still an interesting research area for engineers and researches due to their widespread usage in the vast majority of the rotating machines. There are several techniques for condition monitoring of rolling element bearings. Among them vibration and acoustic measurements are widely used. Tandon & Choudhury review the vibration and acoustic measurement methods employed in the condition monitoring applications of the rolling element bearings. They give a comprehensive literature list and summarize the evaluation methods of vibration signals in time and in frequency domains. They also give the basics of the acoustical emission technique.

2. Rolling Element Bearing Failure

The causes of bearing failures are perhaps as numerous as bearing installations. Tallian and Johruon list the many modes of failure for rolling element bearings, all of which are preventable except fatigue. The cause or mode of failure, defects in rolling element bearings will appear as changes or irregularities in the rolling surfaces of the bearing.

2.1 Contact Fatigue

Contact fatigue is a type of a surface defect or damage that is inevitably related to the operational wear of rolling element bearings. It is generally characterized by spalling, pitting, or flaking off the metallic particles from the rolling surfaces of a bearing, namely outer raceway, inner raceway, and rolling elements. In the context of bearings, contact fatigue is also referred to as rolling contact fatigue because of the rolling and relative sliding movements of the rolling surfaces. (Sarabjeet Singh *et al*., 2015)

2.2 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. (Sham S.Kulkarni, 2013)

2.3 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.

2.4 Overheating

Symptoms are discoloration of the rings, balls, and cages from gold to blue. Temperature in excess of 400^0 F can anneal the ring and ball materials. The resulting loss in hardness reduces the bearing capacity causing early failure.

3. Bearing Characteristics Frequencies

As a defect begins to develop in a rolling element bearing of a machine which is running at certain speed, the vibration spectrum obtained from bearing changes. The occurrence frequencies of the shocks resulted from the defects in the bearings are called bearing defect frequencies or bearing characteristics frequencies. Each bearing element has a bearing characteristic frequency. The peaks will occur in the spectrum at these frequencies due to increase in vibration energy. Initiation and progression of defects or faults on rolling element bearing generate specific and predictable characteristic of vibration. A model presented by Tandon and Choudhury predicted frequency spectrum having peaks at these frequencies. Defects in components of rolling element bearing such as inner race, outer race, rolling elements and cage generate a specific defect frequencies calculated theoretically from the below equations [James Taylor, 1st Edition].

The assumption made that there is no sliding and only pure rolling contact between the rolling elements and the races but in reality there exist some sliding. If there is sliding contact between rolling elements and the races the actual characteristics defect frequencies slightly different from the calculated, but mostly dependent on speed of the shaft, the type of fits and type of bearing.

Table 1 Bearing Characteristics Frequencies

Ball-pass frequency for the inner race (Fi)	BPFI	$\frac{n}{2}\mathrm{Fr}[1 + (\mathrm{BD}/\mathrm{PD})\cos\beta]$
Ball rotational Frequency (Fb)	BRF	$\frac{\mathrm{PD}}{\mathrm{BD}}\mathrm{Fr}\left[1 - \left(\frac{\mathrm{BD}}{\mathrm{PD}}\right)^2 (\cos^2\beta)\right]$
Ball-pass frequency for the outer race (Fo)	BPFO	$\frac{n}{2}\mathrm{Fr}[1 - (\mathrm{BD}/\mathrm{PD})\cos\beta]$
Fundamental train frequency (Ft)	FTF	$\frac{1}{2}\mathrm{Fr}\,[1 - (\mathrm{BD}/\mathrm{PD})\cos\beta]$

Where,
n = No. of balls,
Fr = Shaft Rotation Frequency,
BD = Ball Diameter,
β = Contact angle,
PD = Pitch Diameter

4. Surface Characterization

The quality of machined surface is characterized by the accuracy of its manufacture with respect to the dimensions specified by the designer. Every machining operation leaves characteristic evidence on the machined surface. This evidence in the form of finely spaced micro irregularities left by the cutting tool. Each type of cutting tool leaves its own individual pattern which therefore can be identified. This pattern is known as surface finish or surface roughness.

In the case of bearings, the different manufacturing stages and finishing can vary substantially for each type. The final surfaces obtained from the manufacturers have some amount of roughness called Lower value roughness. While the roughness generated due to extension of local defect on races of ball bearing having Higher value of roughness. So surface defect generated on races falls under the category of higher value roughness.

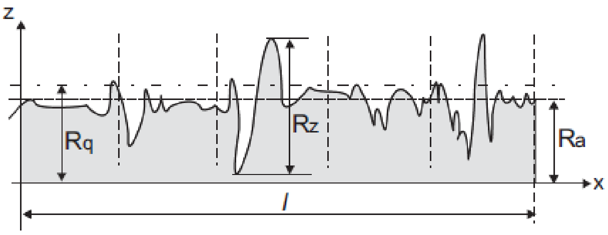

Fig.1 Surface Roughness Profile

Some of the most used parameters, described in the standard ISO 4287 (ASME B46.1) [ISO98f] are (for a roughness profile of length l (μm), height z (μm) and measured over the x direction):

- Ra or simply mean value of the height;
- Rq, the RMS surface height;
- Rz is the mean value of the distance between the highest peak and the lowest valley when the length of the profile is divided in five parts.
- Rsk or skewness, is the measure of the asymmetry of the distribution of heights along the profile.

The parameters Ra, Rq, Rz and Rmax are quantitative parameters, whether Rsk and Rku are both quantitative and qualitative as they also retain information about the shape of the surface.

There are several methods for surface characterization. These are described by Whitehouse and Thomas. An approach to describe surface topography is to treat the profile as an electrical signal and analyze it statistically. The profile is then categorized in terms of the following functions. (B.C. Majumdar, 2013)

1. The probability distribution of ordinate heights

The engineering surfaces finished by metal cutting processes involve the random interaction of cutting girts with surface. Greenwood and Willamson showed that for such surfaces the distribution of heights of the profile was Gaussian.

2. The autocorrelation function of the profile

Some engineering surfaces obtained by certain machining processes contain random and periodic variation of surface heights. Separation of these two variations may be possible by analyzing the two dimensional surface profile autocorrelation functions as defined by

$$\mathbf{F}\,(\boldsymbol{\lambda}) = \lim_{n\to\infty} 1/x \int_{-X/2}^{X/2} y(x)\,y(x+\lambda)\,dx$$

5. Present Theories

McFadden and Smith proposed a vibration models for a single point defect on the inner race of a rolling element bearing under radial load. In this model the vibration is modeled as the product of a series of impulses at the rolling element passing frequency with the bearing load distribution and the amplitude of the transform function, convolved with the impulse response of the exponential decay function. They developed the single point defect model to describe the vibration produced by multiple point defects.

Tandon and Choudhury proposed an analytical model for predicting the vibration frequencies of rolling bearings and the amplitudes of significant frequency components due to a localized defect on outer race, inner race or on one of the rolling elements under radial and axial loads. The defects described with finite width triangular, rectangular and half-sine pulses. The results showed that, when both radial and axial loading exist the outer race defects generates vibration in the outer race defect frequency and its harmonics. For an inner race defects, in the absence of radial loading the vibration generated in the inner race defect frequency. But in the case of both radial and axial loading, the vibration generated in the inner race defect frequency and its sidebands at shaft frequency. They also reported that the vibration level is affected by the pulse shape.

Sopanen and Mikola proposed a dynamic model for a deep-groove ball bearing including localized and distributed defects, effect of internal radial clearance and unbalance excitation of the system. The model considers the Hertzian contact deformation and elastohydrodynamic fluid film in rolling contacts. For the modeling purpose, the shape of the defect is described with the length and the height of the defect. The results of their simulation indicates that both inner ring and outer ring defects generates vibration at their nominal frequencies. They also found that the amplitude of the vibration for similar defects is higher for an outer race defect. This is because the outer ring defect is always in the load zone, and thus the pulse occurs every time a ball passes over the defect.

Sunnersjo C. S. has given clarification about the relationship between geometrical imperfections of the bearing components and resulting pedestal vibrations during operation. A mixed theoretical and experimental impedance approach has been used to treat the bearing when fitted into a simple machine structure. Further, it shows how resulting vibrations of the bearing pedestal can be calculated. It highlights possible methods of condition monitoring and prediction of impending bearing failure. This method is useful for lightly loaded bearings operating at low and moderate speeds. This can be extended to the high speed bearing operating at various conditions.

S P Harsha described an analytical model to forecast non-linear dynamic responses in a rotor bearing system due to surface waviness have been established. In the mathematical modeling the contacts between the races and the rolling elements are considered as non-linear springs, whose stiffness are got by using Hertzian elastic contact deformation theory. The governing differential equations of motion are developed by using Lagrange's equations. The numerical integration technique Newmark-b with Newton–Raphson method is used to solve the nonlinear differential equations iteratively. A computer program is developed to simulate surface waviness of the ingredients.

Stefan Bjorklund has studied the influence of surface roughness on contact behaviour is of great importance in many tribological situations. A problem arising for slender elliptical contacts, such as between roller and raceway, etc., is that the size of the contact is much greater than the size of the asperities. This paper describes a method to calculate the influence of three dimensional surface roughness's in contacts that are very long in one direction. The method is based on restricting the calculations to a subpart of the real contact area, while the rest of the contact is taken into account by mirroring techniques. The results show that the real contact area is very sensitive to the amplitude of the roughness, while the waviness is less important. An equation is suggested from which the real area can be calculated if the smooth case contact parameters and two roughness parameters are known.

G. H. Jang has presented a nonlinear model to analyze the ball bearing vibration due to the waviness in a rigid rotor supported by two or more ball bearings. The waviness of a ball and each race is modelled by the superposition of sinusoidal function, and the position vectors of inner and outer groove radius centre are defined with respect to the mass centre of the rotor in order to consider five degrees of freedom of a general rotor-bearing system. Numerical results of this research are validated with those of prior researchers. It also characterizes the vibration frequencies resulting from the various kinds of waviness in rolling elements, the harmonic frequencies resulting from the nonlinear load-deflection characteristics of ball bearing, and the sideband frequencies resulting from nonlinearity of the waviness interaction.

Ahmad Rafsanjani have presented an analytical model is proposed to study the nonlinear dynamic behaviour of rolling element bearing systems including surface defects. Various surface defects due to local imperfections on raceways and rolling elements are introduced to the proposed model. The contact force of each rolling element described according to nonlinear Hertzian contact deformation and the effect of internal radial clearance has been taken into account. Mathematical expressions were derived for inner race, outer race and rolling element local defects. The results were obtained in the form of time series, frequency responses and phase trajectories. The validity of the proposed model verified by comparison of frequency components of the system response with those obtained from experiments.

Dipen S. Shah was reviews different dynamic models for rolling bearing in presence and absence of local and distributed defects. Moreover, the techniques used for the improvement of fault detection have also been summarized. From a review of dynamic models of healthy and faulty rolling element bearing it has been observed that the vibration amplitude of the defective bearing are more compare to the healthy bearing. Moreover, the presence of bearing fault (local or distributed) and its location can be identified through the time and frequency domain analysis of the vibration signal. The accuracy of the dynamic model depends on the considerations like mass of shaft, bearing elements, housing, linear or non-linear bearing stiffness, lubrication, speed, damping, defect, friction and presence of noise. The defect can be simulated by the addition of extra disturbing force or displacement. The fault detection can be improved by the signal processing techniques.

Sarabjeet Singh made an extensive review of literature concerned with the vibration modelling of rolling element bearings that have localised and extended defects. An overview is provided of contact fatigue, which initiates subsurface and surface fatigue spalling, and subsequently leads to reducing the useful life of rolling element bearings. A review is described of the development of all analytical and finite element (FE) models available in the literature for predicting the vibration response of rolling element bearings with localised and extended defects. Algorithms to estimate the size of bearing defects are reviewed and their limitations are discussed. A summary of the literature is presented followed by recommendations for future research.

Sham S. Kulkarni made an attempt to review the vibration signature analysis of ball bearing with distributed defects on surfaces of inner & outer races. This review found that the effect produced by local defects in stationary condition becomes more severe in non-stationary condition & spreads to form distributed defects. Also 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.

Conclusions

In this paper, an attempt to summarize the recent research and developments in the vibration analysis for diagnosis of rolling element bearing faults has been made. 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 surface defects. In such cases, classical techniques are not more effective to recognize the presence of fault and characteristic frequency.

From the surface characterization, the roughness (i.e. surface defect) generated due to extension of local defect on races of ball bearing having higher value of roughness, which affects the bearing performance. Hence the study of vibration response due to this category of defect is, therefore, important for condition monitoring of ball bearing.

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