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A STUDY OF THE DIAGNOSTIC AMPLITUDE OF ROLLING BEARING UNDER INCREASING RADIAL CLEARANCE USING MODULATION SIGNAL BISPECTRUM

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Abstract. The rolling element bearing is a key part of machines. The accurate and timely diagnosis of its faults is critical for predictive maintenance. Most researches have focused on the fault location identification. To estimate the fault severity accurately, this paper focuses on the study of roller bearing vibration amplitude under increasing radial clearances due to inevitable wear using the modulation signal bispectrum (MSB). The experiment is carried out for bearings with two different clearances for the inner race fault and the outer race fault cases. The results show that the vibration amplitudes at fault characteristic frequencies exhibit significant changes with increasing clearances. However, the amplitudes of vibrations tend to increase with the severity of the outer race fault and decrease with the severity of the inner race fault. Therefore, it is necessary to take into account these effects in diagnosing the size of defect.

Keywords: condition monitoring; radial clearance; contact deformation; bearing defects, MSB

1 Introduction

Rolling element bearings are widely used in rotating machinery and the failure of bearings are the most common reason for machine breakdowns. Defects in bearings are commonly categorized into localized and distributed defects. Distributed defects, such as waviness, surface roughness, or off-size rolling elements, are usually the result of manufacturing errors [1, 2]. Localized defects are often initiated when foreign objects enter into the bearing or when the lubrication film between the surfaces in contact is insufficient. This causes metal-to-metal contact between the rolling elements and the raceways which generates stress waves which in time form surface wear [3]. Wear in rolling bearing appears in many different forms such as, abrasive wear, adhesive wear, fretting wear (corrosion) and false brinelling, which will lead to increase radial clearance. The variation in contact force between rolling elements and raceways due to distributed defects results in an increased vibration level [4-6]. Therefore, the study of the

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bearing vibration response generated by bearing wear is useful for the quality inspection and bearing condition monitoring.

It is well deemed that bearing undergoes various wears during their lifetimes, which leads to large clearances and high vibrations [7]. This high vibration can be good indicators of the remaining life. However, it has not been found that the exact mechanisms on how this increased clearance can effect on the vibration and hence the diagnostic performances. Therefore, this paper focuses on studying the bearing vibration responses with different levels of clearances and clarifies the changes of diagnostic features under difference radial clearances.

2 Internal Radial Clearance

Internal radial clearance is the geometrical clearance between the inner race, outer race and ball. The internal clearance will significantly influence the heat, vibration, noise, and fatigue life. For best rolling element bearing life and machine reliability, internal clearance at running conditions must be close to zero [8, 9]. Moreover, it is also necessary for the purpose of diagnosis to gain the knowledge of changes on the characteristic features when the clearance becomes larger due to the inevitable wear during the bearing service life.

The bearing internal clearance is an important factor because it determines the size of the stressed area of the rings (i.e. the load zone) as shown in Fig. 1. Smaller the clearance (or more the preload), then more and more rolling elements will share the external applied load from the shaft. However, preload may reduce the life of bearings due to high fatigue stresses in rolling elements.

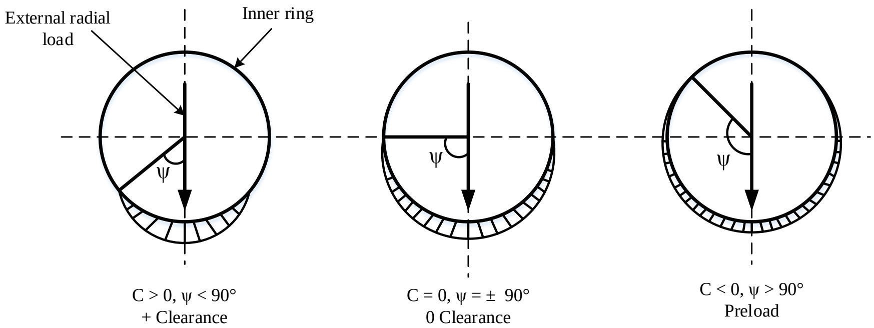

Fig. 1. Rolling element load distribution for different amounts of clearance [3]

The angular contact ball bearings are specifically designed to operate under radial and thrust load, and the clearance built into the unloaded bearing angle. In addition, there are five clearance groups, namely C2, C0 (Normal), C3, C4 and C5. Therefore, the radial internal clearances for radial contact deep groove ball bearing UC206 (6206ZZ) are presented in Table 1 [8].

Table 1. Radial internal clearance for deep groove ball bearing UC06 under no load [8]

Clearance values (μm)									
C2		C0 (CN)		C3		C4		C5	
Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
1	11	6	20	15	33	28	46	40	64

3 Modulation signal bispectrum

MSB has the capability to enhance nonlinear components and suppress random noise by detecting phase coupling in modulation signal. The definition of MSB can be described by Equation (1). [12, 13]

$$B_{MS}(f_c, f_x) = E\left\langle X(f_c + f_x)X(f_c - f_x)X^*(f_c)X^*(f_c)\right\rangle \tag{1}$$

where, $X^*(f)$ is the complex conjugate of $X(f)$ and $E\langle . \rangle$ is the statistical expectation operation, f_c is the carrier frequency, f_x is the modulated frequency and $f_c + f_x$ and $f_c - f_x$ are modulation frequencies. The magnitude and phase of MSB can be expressed as Equation (2) and (3).

$$A_{MS}(f_c, f_x) = E\left\langle \left|X(f_c + f_x)\right|\left|X(f_c - f_x)\right|\left|X^*(f_c)\right|\left|X^*(f_c)\right|\right\rangle \tag{2}$$

$$\varphi_{MS}(f_c, f_x) = \varphi(f_c + f_x) + \varphi(f_c - f_x) - \left|\varphi(f_c)\right| - \left|\varphi(f_c)\right| \tag{3}$$

It takes into account both $f_c + f_x$ and $f_c - f_x$ simultaneously in Equation (10) for measuring the nonlinear effects of modulation signals. If $f_c + f_x$ and $f_c - f_x$ are both due to the nonlinear effect between f_c and, f_x there will be a bispectral peak at bifrequency $B_{MS}(f_c, f_x)$. On the other hand, if these components are not coupled but have random distribution the magnitude of MSB will be close to nil. In this way it allows the wideband noise in bearing vibration signals to be suppressed effectively so that the discrete components can be obtained more accurately.

To enhance the effect of small amplitude sideband, MSB sideband estimator (MSB-SE) [12] was proposed as express in Equation (4)

$$B_{MS}^{SE}(fc, fx) = E\left[\frac{X(f_c + f_x)X(f_c - f_x)X^*(f_c)X^*(f_c)}{\left|X(f_c)\right|^2}\right] \tag{4}$$

Based on MSB property of highlighting modulation effect, a MSB detector can be developed. Firstly, MSB amplitude array is averaged along the f_x direction according to Equation (5) to obtain an average spectrum at different f_c.

$$A_j = \frac{1}{N}\sum_i A_{ij} \tag{5}$$

where i and j is the index of f_x and f_c respectively. Then the carrier frequencies which have high amplitudes are selected as the candidates for feature extraction. Finally, the selected f_c slices are farther averaged to get the MSB detector as expressed by Equation (6).

$$MSBdt = \frac{1}{m}\sum_{j=k_1}^{K_m} A_{ij} \tag{6}$$

where , $j = k_1, \ldots k_m$ is the slice number that selected for calculating MSB detector.

4 Signal processing method

The vibration signals are processed through the following steps: Firstly, calculate the envelopes of vibration signals. Then, the MSB analysis is carried out to enhance the harmonic components in the envelope signals. Finally, the features are extracted at various bearing characteristic frequencies from the MSB. Envelope analysis is the most popular approach for bearing fault feature extraction. However, random noise still exists in the envelope signal. Therefore, MSB analysis is applied to achieve the purpose of denoise and accurately extract the fault features in envelope spectrum [10, 11]. To extract the information from the first three harmonics of fault frequency, f_c is set to the twice of fault frequency, and f_x is the fault frequency. Then, the fault frequency and the third times of fault frequency can be seen as the two sidebands in the modulating signal.

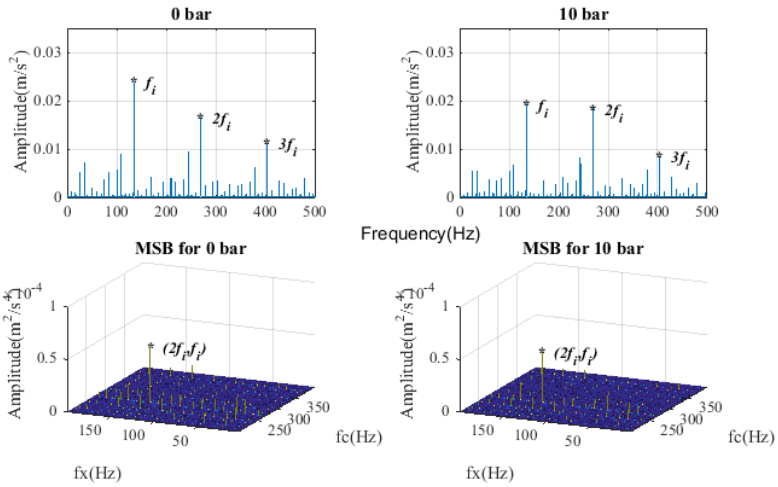

Fig. 2. Envelope spectra and MSB for vibration signals under different loads

Fig. 2 shows the results of envelope analysis and MSB of the vibration signals for 0.2mm inner race fault case under four different radial loads. The four graphs in the first row of Fig. 2 give out the envelope analysis results while the frequency range for filtering is from 3kHz to 10kHz. It is selected according to the power spectrum of vibration signals to cover the whole resonance frequency band of the machine. From the envelope analysis results, it is obvious that much noise exists in the envelope spectra which would influence the accuracy of fault diagnosis. The graphs in the second row illustrate the corresponding MSB results. It can be seen that there is a distinct peak at the bifrequency $B_{MS}(2f_i, f_i)$, which can be used to quantifying the nonlinear characteristics between the harmonic components f_i, $2f_i$ and $3f_i$, corresponding to the envelope spectra.

5 Experiment and fault simulation

The experiment is carried out based on a single-row deep groove ball bearing UC206 (6206ZZ). Fig. 3 shows the simulated bearing faults and sizes on the inner race and outer race. An IEPE type piezoelectric accelerometer with a flat frequency response in the range from 0.5Hz to 5000Hz and sensitivity at 5.106mv/ms2 is used to measure the vibrations. It is mounted on the housing of the test bearing in vertical direction. The experiment was performed at a shaft speed of 1500rpm and under four different radial load conditions at 0, 10, 20 and 30bars. The theoretical calculated fault frequencies for bearing outer race and inner race fault are at 89.8Hz and 134.2Hz, respectively. Two groups of bearings with clearance values of CN and C4 were used to study the fault signature. For each group, one of the bearings is left with no fault and considered as reference bearings. Two types of defects inner race and outer race are artificially induced using electrical discharge machining along the raceways as a rectangular slot with the same depth of 0.2 mm and different width levels as presented in Table 2.

Table 2. Deep groove ball bearing clearance value and defect size measurements

CN (6-20 µm)		
Bearing condition	Clearance (µm)	Defect width (mm)
Small outer race fault	6	0.2
Small inner race fault	13	0.2
Large inner race fault	17.67	0.475
Healthy	8.34	-
C4 (28-46 µm)		
Bearing condition	Clearance (µm)	Defect width(mm)
Small outer race fault	35.72	0.2

Small inner race fault	43.48	0.2
Large inner race fault	43.94	0.475
Healthy	40.85	-

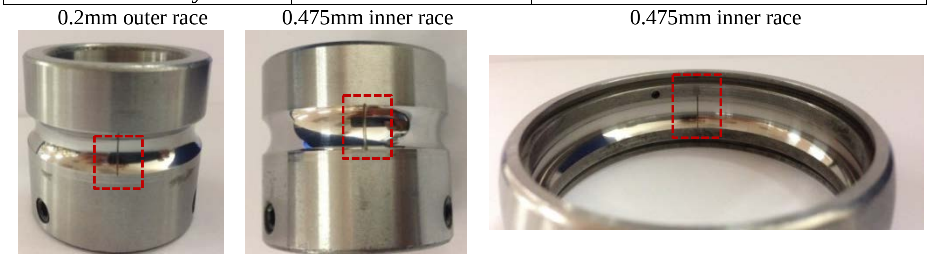

Fig. 3. Photos of fault bearing

6 Diagnostic results and discussion

Fig. 4 shows the results of MSB for all the experimental vibration signals. From the MSB results in Fig. 3, it can be seen that the feature amplitudes for fault cases are distinctively high compared with that of fault-free cases, allowing the fault types to be detected straightforwardly. In the meantime, from the MSBc results it can be seen that the fault frequencies have very high bicoherence amplitudes, which confirms that the detection results from the MSB is very reliable.

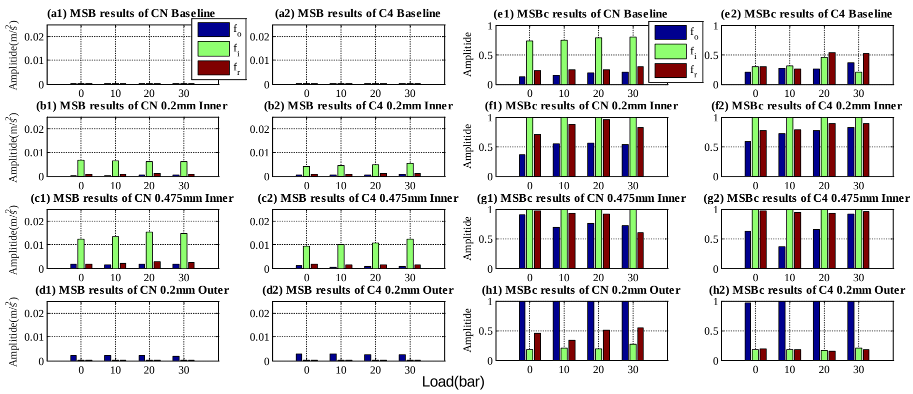

Fig. 4. Fault diagnosis results of MSB and MSBc of vibration signals

To study the influence of clearance, the fault features extracted from MSB results of faulty bearing vibrations with two deferent clearance grades are illustrated in Fig. 5. As expected, the fault frequency amplitude increases with the growth of radial clearance for the outer race defect. However, the amplitude exhibits a decrease for the inner race defect. This decrease is due to the changes in load zone angles. In addition, the outer race fault frequency exhibits lower amplitude compared with the same size of inner race defect, which is caused by the geometric deformation.

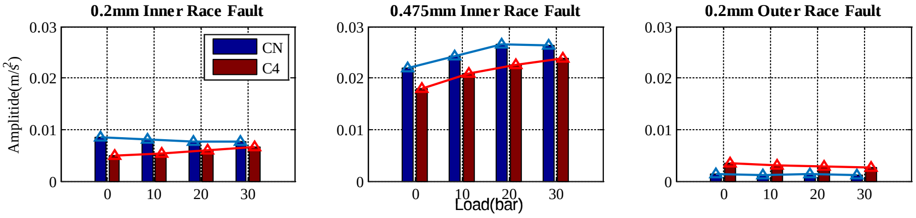

Fig. 4. MSB features of faulty signals

Conclusion

In this paper, the effect of internal radial clearances, which becomes large during the bearing service period due to almost always unavoidable wear, has been studied for accurate detection and diagnosis of roller bearings faults. To obtain reliable detection and diagnosis results, MSB is applied to supress the random noise and extract the harmonic features more accurately from the envelope signals. From the signal processing results, it can be concluded that the fault frequency amplitudes not only change with the fault severity but also influenced by the change of radial clearance as result of load zone angle change. Therefore, during the diagnosis of bearing fault severity, it is necessary to take into account the bearing service duration and bearing clearance grades.

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