Vibration analysis based on the spectrum kurtosis for adjustment and monitoring of ball bearing radial clearance

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Anthimos Georgiadis [1*], *Xiaoyun* Gong [2], *Nicolas* Meier [1]

[1] Leuphana University Luneburg, Luneburg 21339, Germany
[2] Zhengzhou University of Light Industry, Zhengzhou 450002, China

Abstract. Vibration signal analysis is a common tool to detect bearing condition. Effective methods of vibration signal analysis should extract useful information for bearing condition monitoring and fault diagnosis. Spectral kurtosis (SK) represents one valuable tool for these purposes. The aim of this paper is to study the relationship between bearing clearance and bearing vibration frequencies based on SK method. It also reveals the effect of the bearing clearance on the bearing vibration characteristic frequencies This enables adjustment of bearing clearance in situ, which could significantly affect the performance of the bearings. Furthermore, the application of the proposed method using SK on the measured data offers useful information for predicting bearing clearance change. Bearing vibration data recorded at various clearance settings on a floating and a fixed bearing mounted on a shaft are the basis of this study

1 Introduction

Rolling element using bearings are widely used in rotating machines. Their condition drastically influences the performance of the whole machine or production line. Also in the construction and energy sectors such rolling elements with bearings play an important role. Therefore, the detection of bearing faults as well as wear monitoring have always received intense research interest. O'Donnell (1985) [1] identified bearing faults as the most common ones in a statistical evaluation on the reliability of large motors in industrial and commercial installations. Later analyses by Singh and Ahmed Saleh Al Kazzaz (2003) [2], Bellini et al. (2008) [3] on induction machines confirmed this insight and gave an overview on diagnostic techniques for fault detection based on vibration analysis and current signal analysis. Feiyun Cong *et al*. (2010) [4] combined SK with Autoregressive AR for fault diagnosis and condition monitoring of bearings. Len Gelman *et al*. (2013) [5] used another combination of spectral kurtosis and wavelet transform for rolling bearing diagnosis. A more recent summary on fault modelling and predictive health monitoring for rolling element bearings by El-Thalji and Jantunen (2015) [6] lists a comprehensive overview of research done in this field. Accordingly, artificially introduced mechanical defects are easier to detect than faults in industrial applications. Normally, bearing faults evolve slowly and are hard to detect at an

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[*] Corresponding author: georgiadis@leuphana.de

early stage. Therefore, most diagnostic techniques based on vibration analysis focus on the detection of major mechanical defects, rather than monitoring the actual bearing condition. However, one parameter influencing the condition of rolling-element bearings is the radial clearance; defined in Brändlein (1999) [7] as the maximum displacement, that outer and inner ring of the bearing can move in relation to one another in radial direction. Ganesan (1996) [8]; Tiwari *et al.* (2000b) [9]; Sopanen and Mikkola (2003) [10] found that the clearance affects the bearing stiffness and therefore, the rotor stiffness and dynamic rotor response of induction machines. An increasing clearance leads to a decreasing stiffness. Furthermore, Oswald *et al.* (2012) [11]; Nguyen-Schäfer (2016) [12] pointed out that the internal clearance strongly affects load distribution as well as wear and therefore, the fatigue life of radially loaded deep-groove ball and cylindrical roller bearings. In order to enhance the durability of rolling element bearings, the internal clearance is adapted to the load case as described above and cannot be measured or re-adapted without dismounting the bearing from the housing. Anyhow, the clearance can change over time or during operation. Tiwari *et al.* (2000a) [13]; Sopanen and Mikkola (2003) [10]; Cao and Xiao (2008) [14] studied the frequency spectra of the vibration caused by rotating bearings experimentally with respect to the clearance. These publications reported peaks in the frequency spectra at the rotation frequency f_r and the roller passing frequency, sometimes referred to as varying compliance, as well as all their harmonics and linear combinations. Sopanen and Mikkola (2003) [10]; Cao and Xiao (2008) [14] compare the vibration spectra of two bearings with different clearances and observe that the vibration amplitudes increasing for higher radial clearance. Rolling bearings encounter various types of wear during their lifetime, which can lead to large radial clearances and high vibration levels. Rehab Ibrahim found out in his doctoral thesis 2016 at the University of Huddersfield [15], those changes in clearance significantly affect the fault diagnosis. The aim of this work is to develop a method for in-situ bearing clearance measurement for their adjustment and monitoring, using vibration analysis based mainly on SK.

2 Theoretical background and proposed method

Bearing vibration frequencies can be determined from the bearing geometry, as published in a Brüel & Kjær Technical Report by Angelo (1987) [16] and later by Vas (1993) [17]. The fundamental train frequency relative to the outer ring f_{fto} is defined in Eq. (1) and depends on the rotation frequency of the shaft f_r as well as the bearing geometry parameters; ball diameter d_b, pitch diameter d_p and contact angle β

$$f_{fto} = \frac{1}{2} f_r \left(1 - \frac{d_b cos\beta}{d_p} \right) \tag{1}$$

The clearance influences the bearing characteristics and therefore, the vibrations during service. As the contact angle of double-row self-aligning ball bearings is generally in the range of 5° to 20° (Schaeffler Technologies AG & Co.KG (2015))[18], its cosine decreases as depicted in Eq. (1). Furthermore, the pitch diameter in this model increases by $c/2$, which also leads to a rising f_{fto}.

The value of kurtosis in time domain normally detects the degree of impulsiveness in gearbox or rolling bearings from vibration data. Kurtosis is defined as:

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

where x is the sampled time signal, i is the sample index, N is the number of samples, $\bar{x}$ is sample mean.

The SK can indicate the presence of the optimal frequency and bandwidth for non-stationary vibration signal. According to Antoni [19], is function of time and frequency, and the 2n-order spectral moment defined as:

$$S_{2nY}(f) = \langle S_{2nY}(t,f) \rangle_t \tag{3}$$

where $\langle S_{2nY}(t,f) \rangle$ denotes the time averaged operator of the 2n-order instantaneous moment. $C_{4Y}(f)$ is the fourth-order spectral cumulant. The SK at each frequency is obtained by Eq. (4):

$$K_Y(f) \triangleq \frac{C_{4Y}(f)}{S_{2Y}^2(f)} = \frac{S_{4Y}(f)}{S_{2Y}^2(f)} - 2, \quad f \neq 0 \tag{4}$$

3 Experiment

The experimental setup is illustrated in Figure . While bearing 1 is floating, bearing 2 is fixed. The vibration sensors are mounted at each housing. The sampling frequency is 392 Hz and the rotation frequency is f_r. All components used in this setup are listed in **Error! Reference source not found..** The sizes of the bearings are listed in **Error! Reference source not found..**
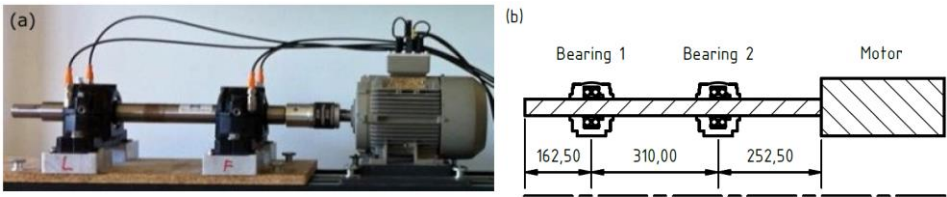

Figure 1. Experimental setup: Floating (bearing 1) and fixed (bearing 2) bearings mounted on a shaft for experiment. (a) Photograph. (b) CAD model, sectional view.
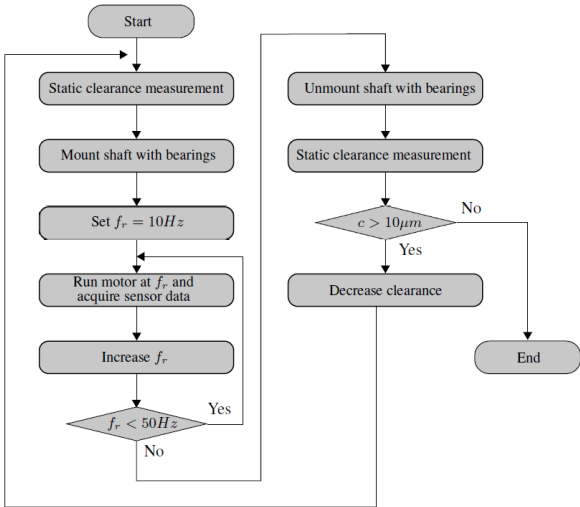

Figure 2. Block diagram of experimental procedure.

Table1: Components used in the experimental setup.

Bearings	NTN 2309SK
Adapter sleeves	NTN H2309
Locating ring	NTN FR100x4
Bearing housings	NTN SNC 511-609
MEMS sensors	IFM VSA001
Piezo sensors	IFM VSP001
Data acquisition system	IFM VSE100
Three-phase motor	Siemens 1LA5090-4AA60-Z
Frequency converter	Siemens SIMOVERT 6SE2103

Table2: Geometry parameters of the ball bearings NTN 2309SK.

Outer diameter D	100mm
Bore diameter d	45mm
Width B	36mm
Ball diameter db	15.87mm
Pitch diameter dp	71.81mm
Contact angle β	15.52°

Fig. 2 describes the experimental procedure. Before starting, the initial radial clearance c of bearing 2 is measured, as described in Meier and Georgiadis (2016, 2017a, 2017b) [20-22].

After acquiring this first set of data, the rotation frequency is set to the next value (15 Hz) and the next set of data for another 10 minutes. This procedure is successively repeated for the rotation frequencies of 20; 25; 40 and 50 Hz. After these first six experiments, the shaft with the bearings is unmounted from the setup to measure the radial clearance after experiment c_2 and the clearance change is defined as $\Delta c = c - c_2$. Afterwards, the procedure is repeated for the same six rotation frequencies. The experiment is successively performed for all five different set clearances $c = \{46.2, 41.2, 34.3, 20.8, 7.8\}$ μm. The clearance at the floating bearing is not changed nor measured. Combinations of 30 different clearances and rotation frequency and the kurtosis at 3 typical operating conditions are performed in this work.

4 Results of SK

We tested the proposed method at clearance of 34 μm at rotating speed 10 Hz, 25 Hz and 50 Hz. The bearing vibration signal band is [0 Hz, 196 Hz] in level 0, as shown in the Fig. 3. The peaks are at approximately $5f_{fto}$ Hz (the bearing fundamental train frequency f_{fto} is around 3.9 Hz). There are the prominent peaks at 18.03 Hz, 48.63 Hz and 98.78 Hz. They agree to the corresponding theoretical results of bearing characteristic frequency and its harmonics. Fig. 4 shows that the kurtosis peak value of amplitude spectrum increased obviously with increasing speed. It changes linearly with the frequency, but the transform is the same with the various clearance. The localized peak frequencies around $5f_{fto}$ are plotted versus the bearing clearance at rotating speed 10 Hz, 25 Hz and 50 Hz, as shown in Fig. 5. The curves show a good linear progression for rolling bearing train frequency f_{fto} over a range of bearing clearance. The frequency shift is fitted with a linear regression model.

To compare the results of the presented method in this paper, the kurtosis of 3 kinds of different speeds under 5 different bearing clearances were analysed in Fig. 6. According to the analysis results of kurtosis value at bearing different clearance, it can be seen the phenomenon of instability.

5 Conclusions

The application of the SK method was proven as a powerful tool for bearing fault detection. The results show a correlation between kurtosis index at vibration characteristic frequency and bearing clearance. Further, they show that the kurtosis values in time domain of bearing vibration signal are unstable. The kurtosis in time domain of rolling bearing is dependent on the bearing clearance. The SK method can restrain the noise and analyse the components of the bearing train frequencies in the envelope spectrum. Using the SK method has advantages on extracting kurtosis peak value at characteristic frequency. The proposed method reflects more the relationship between kurtosis values and rotating speed than time domain kurtosis.
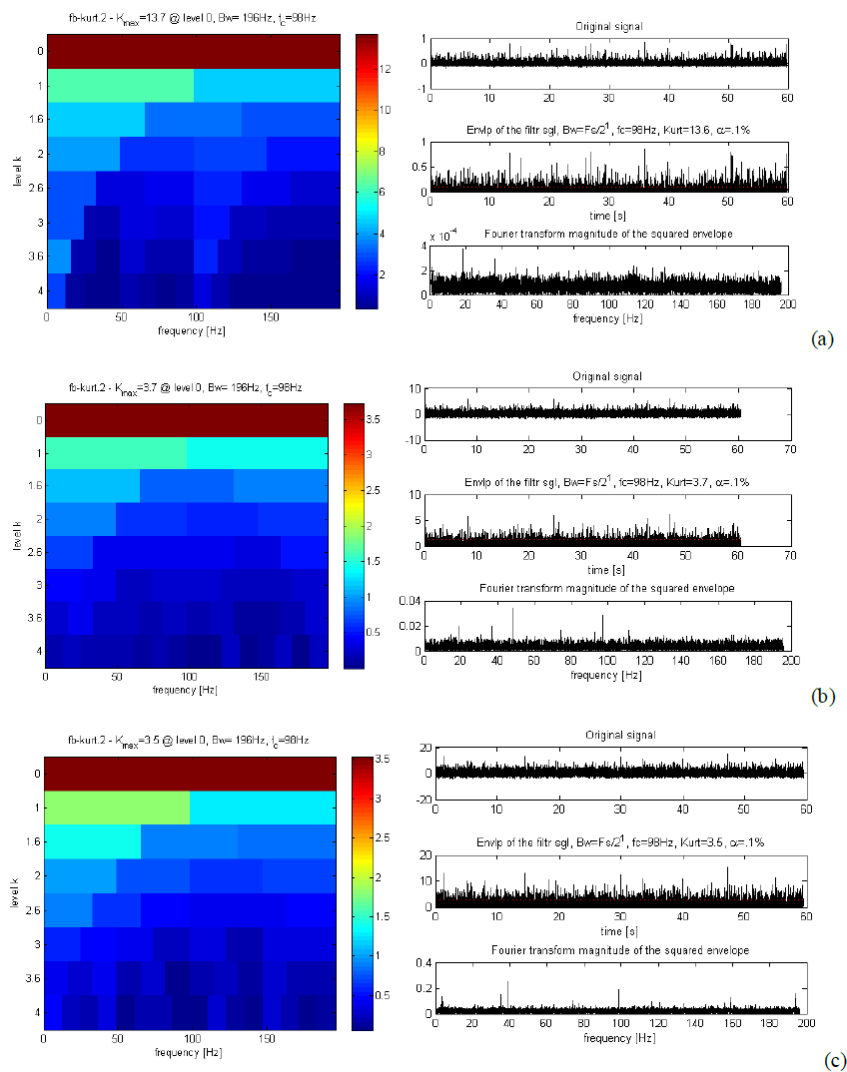
Figure 3. The results of spectrum kurtosis for rotation speed of: (a) 10 (b) 25 (c) 50 Hz.
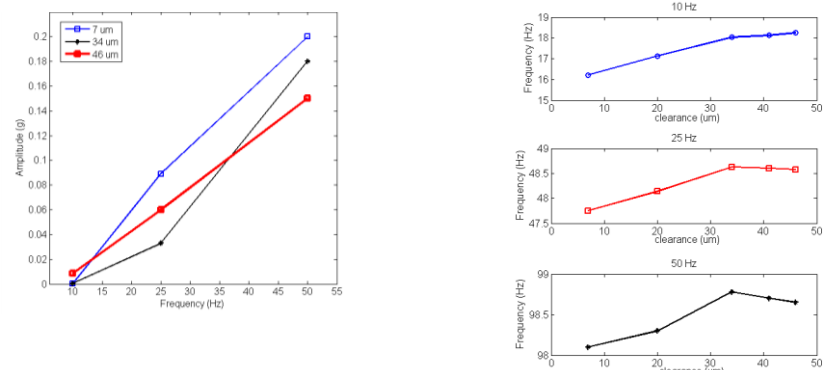

Figure 4. SK values at different rotating frequency. **Figure 5.** Change of $5f_{fto}$ at different clearance.
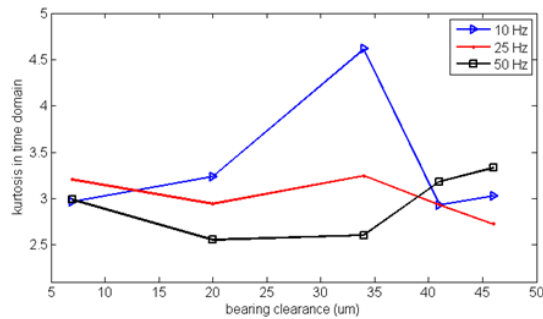
Figure 6. Kurtosis in time domain at different clearance.

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