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

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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
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 & Kjaer Technical Report by Angelo (1987) [16] and later by Vas (1993) [17]. The
fundamental train frequency relative to the outer ring \( f_{to} \) 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 \( \beta \)

\[
f_{to} = \frac{1}{2} f_r \left(1 - \frac{d_b \cos \beta}{d_p}\right)
\]  

(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 \( f_{to} \).

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:

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

(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:

\[ S_{2nY}(f) = \langle S_{2nY}(t, f) \rangle_t \]  

(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):

\[ K_Y(f) \equiv \frac{C_{4Y}(f)}{S^2_{2Y}(f)} = \frac{S_{4Y}(f)}{S^2_{2Y}(f)} - 2, \quad f \neq 0 \]  

(4)

3 Experiment

The experimental setup is illustrated in Figure 1. 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](image1)

**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](image2)

**Figure 2.** Block diagram of experimental procedure.

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].

| Table1: Components used in the experimental setup. |
|--------------------------------------------------|
| Bearings | NTN223105K |
| Adapter sleeves | NTN23209 |
| Locating ring | NTNFR106x4 |
| Bearing housings | NTN32C511-660 |
| MEMS sensors | IFM-VX1001 |
| Piezo sensors | IFM-VSP001 |
| Data acquisition system | IFM VSE100 |
| Three-phase motor | Siemens LA5090-4AA60-Z |
| Frequency converter | Siemens SIMOVERT 6SE2103 |

| Table2: Geometry parameters of the ball bearings NTN 2305SK. |
|-------------------------------------------------------------|
| Outer diameter \( D \) | 100mm |
| Bore diameter \( d \) | 45mm |
| Width \( B \) | 36mm |
| Ball diameter \( db \) | 15.87mm |
| Pitch diameter \( dp \) | 71.81mm |
| Contact angle \( \beta \) | 15.52° |
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 $5f_{tto}$ Hz (the bearing fundamental train frequency $f_{tto}$ 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 $5f_{tto}$ 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 $f_{tto}$ 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.

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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 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.

### 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 $5f_{rot}$ Hz (the bearing fundamental train frequency $f_{rot}$ is around 3.9 Hz). The principal peaks are 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 $5f_{rot}$ 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 $f_{rot}$ 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.

### Conclusions

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Figure 6. Kurtosis in time domain at different clearance.

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