# Monitoring of the Damage in Rolling Element Bearings

**Steven Chatterton, Pietro Borghesani, Paolo Pennacchi and Andrea Vania**

**Abstract** Envelope Analysis of vibration signal is the most used and simplest method for the diagnostics of rolling element bearings. This method is based on the identification of bearing damage frequency components in the so-called Envelope Spectrum. If the recognition of the damage type is quite a simple task, the monitoring and the evaluation of the trend of a suitable damage index are complex tasks to be performed in an automatic way. The damage index must be robust against variations of system operating conditions and external vibration sources to avoid misleading results. In the paper, the case of a rolling element bearing in which the defect develops until a permanent failure is described as well as the algorithm implemented for alarm signaling.

**Keywords** Rolling element bearing · Envelope analysis · Square envelope spectrum · Bearing damage

## 1 Introduction

Rolling Element bearings (REBs) are often subjected to heavy operating conditions and aggressive environments and, therefore, they are prone to failure.

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In the literature, most of the papers concerning bearing diagnostics, are focused on signal processing techniques applied to vibration measurements. Many different techniques have been developed for the detection of bearing damages [1]: from Envelope Analysis-EA up to recent developments of Square Envelope Spectrum-SES [2], 2nd order cyclostationary analysis [3, 4], Spectral Kurtosis-SK [5], Empirical Mode Decomposition-EMD [6] and Minimum Entropy Deconvolution-MED [7, 8]. Among these, the most used and simplest method for the assessment of the bearing health is the EA that is based on the identification of bearing damage frequency components in the so-called SES. The main critical point of this technique is the selection of a suitable frequency band for the demodulation of the vibration signal.

The selection of the frequency band, is based on the analysis of the peakedness of the analytical signal, by means of the Kurtosis index. The value of Kurtosis for a signal having a complex normal distribution is equal to 2.

Usually, the definition of the frequency band based on the band-Kurtosis (BK), that is the Kurtosis index of a filtered signal, is performed by mean of the Fast Kurtogram diagram, proposed for the first time by Antoni [9], or by more recent Protrugram by Barszcz and Jablonski [10], in which the value of BK is reported as function of the central frequency for a fixed bandwidth.

The constancy in the time of this optimal frequency band is also critical. In general, the constancy of this optimal band during the whole bearing life is particularly desirable. External phenomena, such as the temperature gradient of the bearings, can change the optimal bands suggested by the two diagrams.

The same BK index is assumed in the paper as damage indicator. Its simplicity allows the evaluation in the case of real-time applications. In the paper, the case of a rolling element bearing, in which the defect develops until a permanent failure, is described as well as the algorithm implemented for alarm signaling.

Vibration data are collected at a fixed time interval of 1 h. Current trend in industrial field is the adaptive monitoring in which the periodicity of the vibration measurement is varied accordingly to the trend of the damage indicator [11, 12].

## 2 Failure Description

In the paper, the damage occurred to one of the rolling element bearings of the frame supporting the output shaft of a train gearbox, shown in Fig. 1, is described.

This bearing was monitored by an accelerometer and a temperature dual-probe. After a period of about 39 millions of bearing cycles from the beginning of the experimental activity, high level of vibration had been detected by the sensor. The inspection revealed a severe damage of the bearing, mainly located in the inner ring with quite a number of brinelling marks, as shown in Fig. 2.

The damage was caused by an angular misalignment of the shaft with respect to the bearing house due to looseness of the frame support. In this operating condition, a local bearing overload occurred, leading to the premature failure.

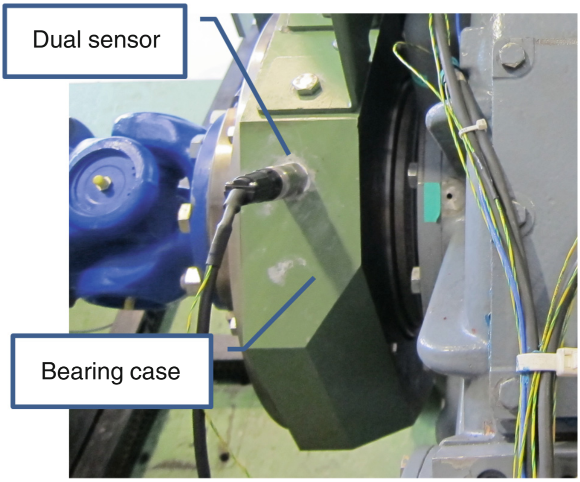


**Fig. 1** Bearing case and position of dual sensor

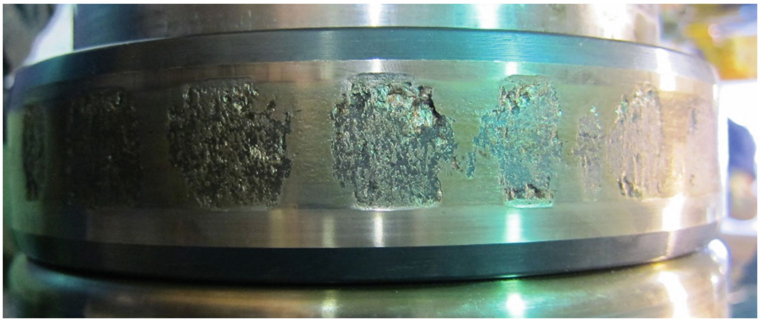

**Fig. 2** Inner ring of the damaged bearing after dismounting

Unfortunately, it was not possible to identify the time in which the misalignment of the shaft occurred. However, from the analysis of the vibration data acquired by the sensor it was possible to identify an increase of the damage indicator at about 5 millions of cycles in correspondence of a maintenance operation of the system. The bearing had been ran for about 100 days, for about 8 h in each day, at constant speed of about 970 rpm and constant radial load until the failure. After the failure, the bearing had been replaced.

## 3 Vibration Signal Analysis

The following algorithm has been used for the analysis of the vibration signal:

1. pre-evaluation of the signal on the basis of the gradient of the temperature. The first acquisition of each day is performed at cold temperature after about 10 min

from the start-up of the system. In this condition, the Kurtosis index is unstable. This suggests discarding vibration data when acquired in not a thermal steady state. The gradient of the temperature can be used as index of the thermal steady state. In the case analyzed in the paper, the system reached the steady state after about 2 h where the temperature gradient is less than 5 °C/h. The absolute value of the temperature is misleading due to the daily and seasonal variation of the room temperature, which oscillates between about 15 and 40 °C during the experimental activities.

2. band filtering of the signal in a suitable frequency band;
3. evaluation of damage level by means of the BK index of the analytic signal as function of time or cycles;
4. assessment of the damage type by the identification of damage bearing frequencies in the SES of the analytic filtered signal;
5. estimation of the Residual Useful Life (RUL) of the bearing on the basis of the Root Mean Square (RMS).

## 3.1 Band Filtering

The frequency band of the filter is characterized by two parameters: the bandwidth and the central frequency. The filter band has been selected on the basis of the maximum value of the BK. The trend of these two parameters in which the BK is maximum, is reported in Fig. 3 in a diagram called by the author “KurtoMap”. It is

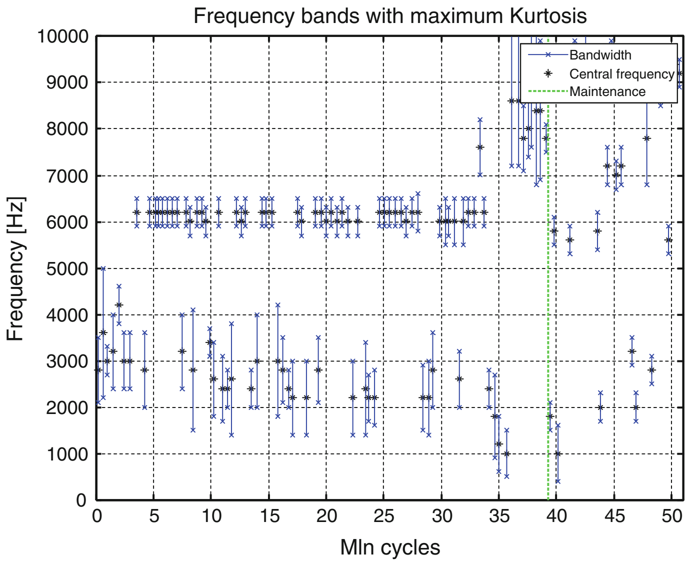


**Fig. 3** KurtoMap for the frequency band selection

possible to observe two clusters: the first at a central frequency of 6,100 Hz and bandwidth of 1,000 Hz is assumed in the paper for tracking the damage index; the second at a central frequency of 2,500 Hz and bandwidth of 2,000 Hz.

## *3.2 Evaluation of Damage Level*

The core of the algorithm is represented by the trend of BK index and RMS as shown in Fig. 4. In the figure, vibration data correspond to the 5th hour of test of each day when the system reached the thermal steady state. The optimal filter band is 5,625–6,875 Hz. The bearing has been replaced during the maintenance performed at about 39 millions of cycles.

By considering the BK and the RMS of the signal in Fig. 4, it is possible to identify two main stages of the damage evolution. The early stage lasts for about 34 millions of cycles. In this stage the BK deviates from the standard value of 2 to quite a constant value of 2.7, whereas the RMS value of the signal is very low.

The deviation from the standard value of 2 could be assumed as symptom of the damage growth. A threshold of 10 % with respect to the standard value of 2 could be used as alarm indicator. The transition between light and severe damage is indicated by simultaneous a drop of BK and an increase of RMS.

After the replacement of the damaged bearing with a new one (at about 39 millions bearing cycles), the BK index return within the threshold of 10 % with respect to the standard value of 2.

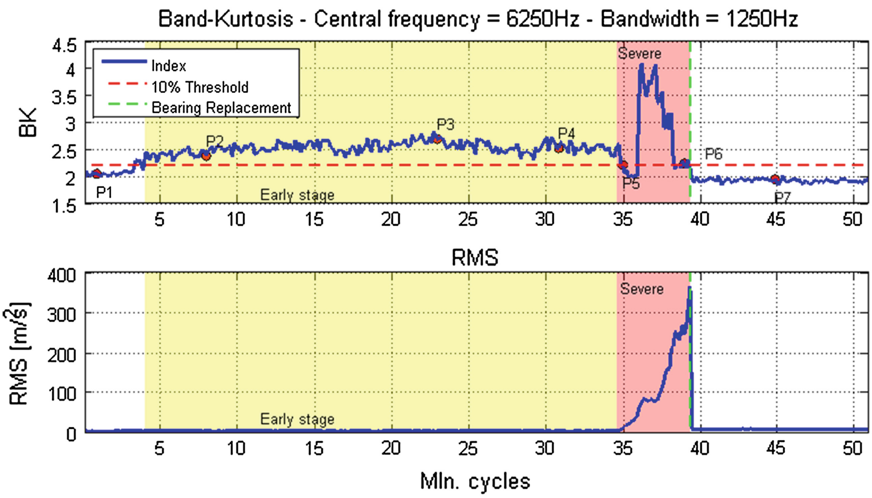


**Fig. 4** Trend of BK and RMS values

The RMS of the filtered signal cannot give the same information provided by BK index. In the first part of the trend in Fig. 4, until about 34 millions of cycles, the RMS is quite equal to zero.

### 3.3 Damage Type

The assessment of the damage type is based on the identification of fundamental defect frequencies of the bearing in the spectrum of the processed signal. The theoretical values of these frequencies depend only on the geometry of the bearing and represent the frequency of consecutive impacts of the defect on the rolling elements. Actual values of these frequencies are different from the theoretical ones. A frequency-shift, the "jitter", due to the actual kinematic contact among the elements of the bearing and depending mainly on the bearing load appears in real cases as described in [2, 13] and [14]. The following theoretical damage frequencies for the SKF NU1040M bearing running at 16.17 Hz are:

- Ball Pass Frequency Inner ring (BPFI) = 213.44 Hz;
- Ball Pass Frequency Outer ring (BPFO) = 174.64 Hz;
- Fundamental Train Frequency (FTF) = 7.28 Hz;
- Ball Spin Frequency (BSF) = 78.42 Hz.

Knowing the theoretical bearing defect frequencies, it is possible to identify the type of the bearing damage (inner ring, outer ring or rollers) by means of the SES [15–17].

The SESs of the analytic filtered signal are reported in Fig. 5 for different bearing cycles corresponding to several points indicated in Fig. 4. It is possible to observe in Fig. 5 the clear presence of cyclic frequency component close to the theoretical BPFI reported in dotted red line.

### 3.4 Estimation of the Residual Useful Life

As already said the RMS of the filtered signal cannot give the same information provided by BK index in the early stage of the damage, where its values is quite equal to zero till about 34 millions of cycles.

On the contrary, the RMS can give information for the second stage of the damage, where it is possible to forecast the residual useful life (RUL) of the bearing. In particular it is possible to interpolate RMS data samples by means of an exponential curve using different sets of samples:

$$y(c) = A \cdot e^{B \cdot (c - c_0)} \tag{1}$$

where $c$ is in millions of cycles, and $c_0$ is the starting point of interpolation where the BK drops (at 34.9 millions of cycles).

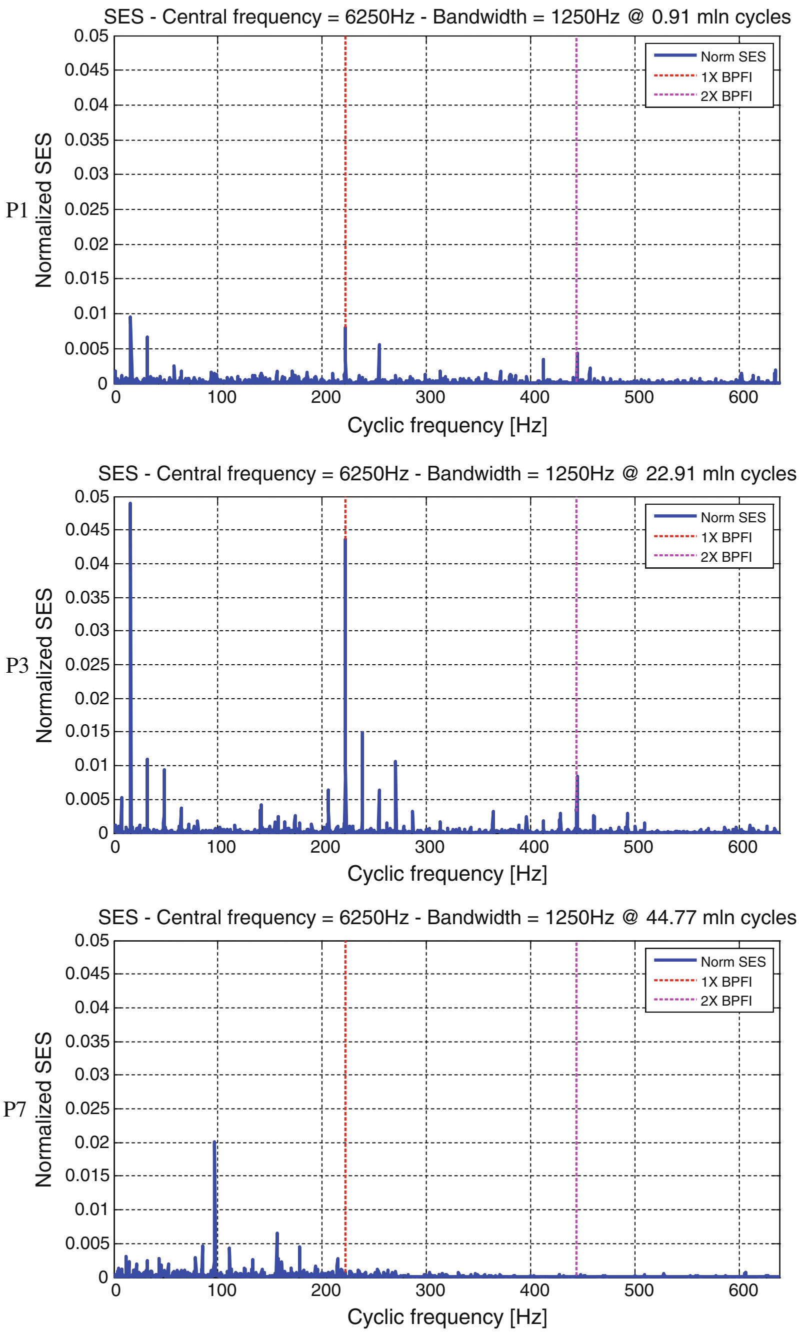


**Fig. 5** Square Envelope Spectra for several bearing cycles

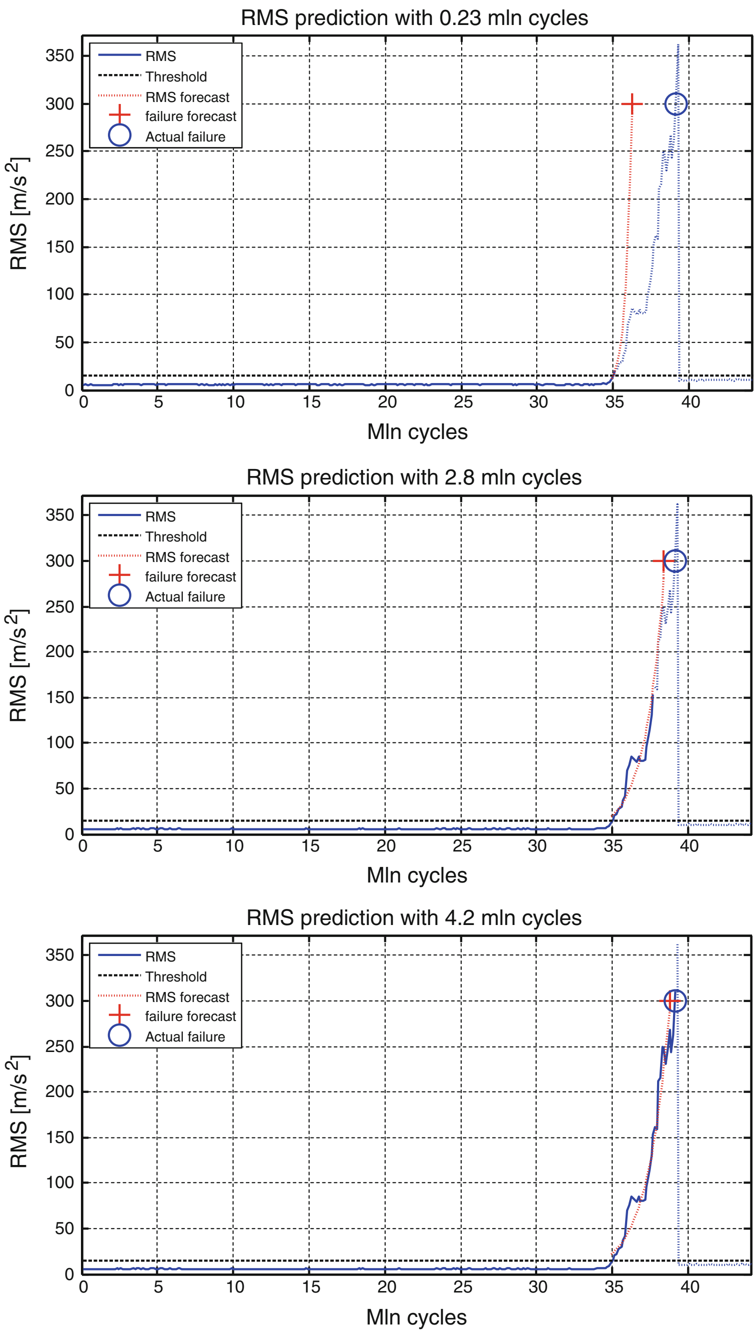


**Fig. 6** Forecast of bearing residual useful life as function of bearing cycles

For instance, sets of 0.23, 2.8, and 4.2 millions of cycles are considered for the interpolating red dotted curve in Fig. 6, where a threshold of 300 $m/s^2$ is assumed as index of failure. The actual RMS curve is also reported in blue line. Obviously, the accuracy of estimation is better as the number of sample increases.

## 4 Conclusion

The problem tracking the level of damage in rolling element bearings has been discussed in the paper and an algorithm has been proposed as well.

The algorithm is based on an optimal use of standard tools as Envelope Analysis and Kurtosis index. The algorithm has been tuned and validated by means of experimental data of a failure occurred in an industrial rolling element bearing.

Eventually the estimation of the residual useful life on the basis of RMS value is also proposed.

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