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# VIBRATION ANALYSIS OF ROLLING BEARINGS

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## ABSTRACT

*Machine failures in modern industry led to decreased production and reduced competitiveness. Bearings are important parts in machine construction and their operation has a significant impact on the function and lifespan of the machine as a whole. Vibration measurement is the main non-invasive method for locating and predicting failures of rotating machinery components. The paper details using vibration analysis, specifically Power Spectral Density (PSD) analysis of acceleration signals from a bearing's damaged inner race, as a cost-effective and reliable method to diagnose bearing failures. This technique identifies deviations from normal vibration patterns in rotating equipment, helping to predict and prevent potential failures.*

KEYWORDS: bearing, vibration, defect, signal processing, power spectral density

## 1. INTRODUCTION

The causes that lead to the appearance of vibrations in the operation of elements in rotational motion are multiple and refer to: fatigue, wear, plastic deformation, corrosion, brinelling, lubrification, faulty installation, incorrect design etc. Each of these factors will influence in specific mode the behavior of the rotative elements motion, especially the vibration spectrum of monitored signal. In this context, has become widespread the signal processing which represents a field that analyzes signals (including vibrations) to obtain useful information, most often for fault diagnosis and detection of non-conformity in operation. For example, vibration signals, characterized by their periodic motion and their harmonics that represent the storage and absorption of energy, are useful features for detecting problems in rotating machinery. Since the mid-1980s, the first applications of vibration analysis in the detection of gear faults have been known [1,2]. The specialized literature refers to various data processing techniques used to extract information about faults from the recorded raw vibration signal, classify faults according to their severity, and fault prediction models developed for gears, bearings, etc. [3-5].

The most popular method used by vibration-based diagnostic experts for condition monitoring of a mechanical element is the spectral component analysis method [6,7].

## 2. BEARING FAULTS

Rolling element bearings being in optimal operation condition generate vibrations due to the changing stiffness of the bearing assembly as the rolling elements rotate underload during the technological process. Therefore, this varying compliance is a natural phenomenon, and this operation mode is not necessarily indicative of a bearing defect. Localized bearing faults, which are small, concentrated areas of damage on bearing surfaces, can indeed occur on either the outer race, on the inner race, and on the rolling elements of the bearing. These faults typically start as small pits or spalls and can cause noticeable vibrations as the rolling elements pass over them [8, 9]. Each of these faults is characterized by their natural frequency, which is usually specified by the manufacturer or calculated in the technical specification of the bearing.

An impact from a localized fault generates high-frequency vibrations in the gearbox structure or in driven systems of technological equipment. In the case of an outer race defect, the amplitude of the component at the defect frequency is much higher compared to those generated by the inner race defect or by the rolling element defect of the same size and under similar load and speed conditions [10].

A classic technique for analyzing bearing vibration signals is shown in figure 1.

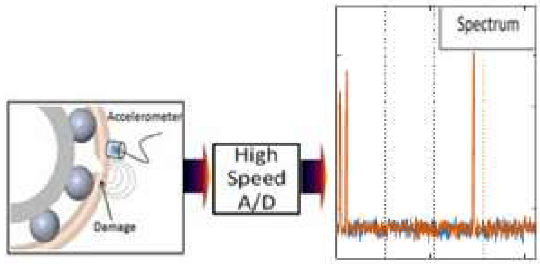


Fig. 1 Bearing fault detection vibration analysis [11,12]

Over their lifetime, bearings operate in four specific stages of vibration characteristics as the defect increases, as can be seen in the schematic in Figure 2.

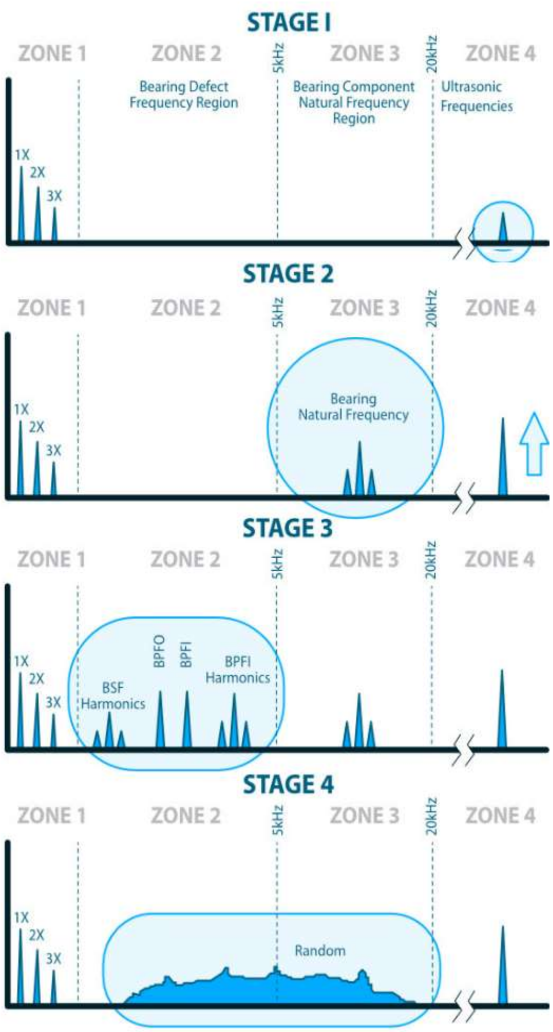


Fig. 2 Indicators of the extent of the deterioration of the bearing [13]

## 3. THEORETICAL CONSIDERATIONS

A bearing's construction typically involves two rings (inner and outer), rolling elements (balls or rollers), and a cage to separate the rolling elements. A schematic of the construction of a bearing is detailed in figure 3.

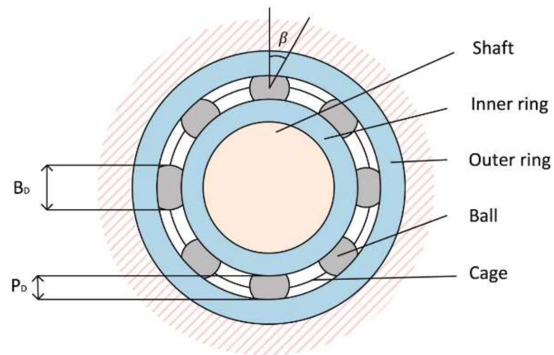


Fig. 3 Typical structure of a ball bearing [8]

The characteristic defect frequencies are calculated function by geometric dimensions of the bearing, number of balls and shaft frequency as given below [13,14]:

a) Ball Pass Frequency Outer Race (BPFO):

$$BPFO = \frac{n}{2} \cdot \frac{RPM}{60} \cdot \left(1 - \frac{B_d}{P_d}\right) cos\beta, \quad (1)$$

b) Ball Pass Frequency Inner Race (BPFI):

$$BPFI = \frac{n}{2} \cdot \frac{RPM}{60} \cdot \left(1 + \frac{B_d}{P_d}\right) cos\beta, \quad (2)$$

c) Pass Frequency Rolling Element (BPFR):

$$BPFR = \frac{P_d}{2B_d} \cdot \frac{RPM}{60} \cdot \left[1 - \left(\frac{B_d}{P_d}\right)^2 cos^2\beta\right]. \quad (3)$$

where: $B_d$ - ball diameter;
$P_d$ - pitch diameter;
$n$ - number of balls; $\beta$ - contact angle.

We consider a bearing with following parameters centralized in Table 1.

Table 1. Data for bearing identification

| No. | Parameter | Symbol | Value |
|---|---|---|---|
| 1 | Ball diameter | $B_d$ | 0.02 m |
| 2 | Pitch diameter | $P_d$ | 0.14 m |
| 3 | Number of balls | $n$ | 8 |
| 4 | Contact angle | $\beta$ | $20^0$ |

After signal processing using MATLAB, we have several analysis options as follows: frequency domain and power spectrum analysis and, respectively, the spectrogram analysis which is generated by applying the windowed STFT to the input signal (fig. 4).

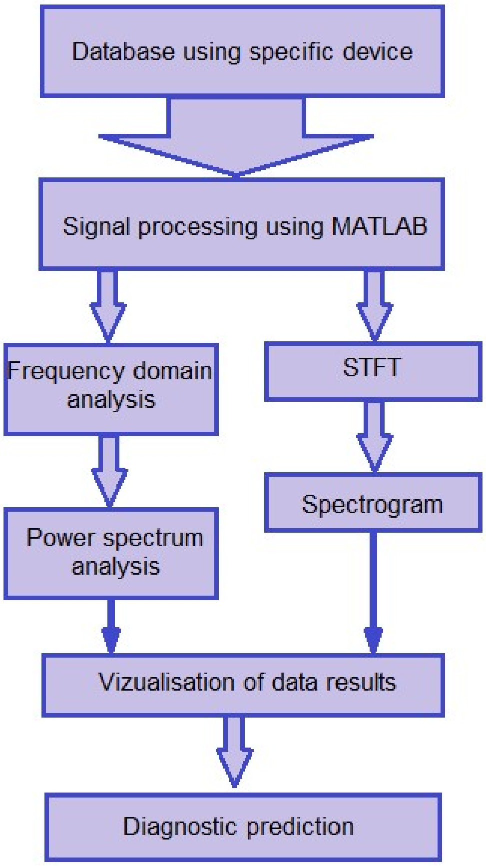


Fig. 4 Example of a flowchart for data acquisition and analysis

Envelope and phase can be extracted from the analytic signal as follows:

$$a(t) = \sqrt{x^2(t) + \tilde{X}^2(t)}, \quad (4)$$

$$\theta(t) = tan^{-1}\left[\frac{\hat{x}(t)}{x(t)}\right], \quad (5)$$

where:

$$\hat{x}(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{x(t)}{t-\tau}d\tau, \quad (6)$$

$$\tilde{X}(t) = X(t) + j\hat{x}(t) = a(t)e^{j\theta t}. \quad (7)$$

Notations depicted into Eq. (4) and (5) are next significations: *x(t)* – signal in time domain; $\hat{x}(t)$ – Hilbert transform in frequency domain of *x(t)* signal; $\tilde{X}(t)$ - complex signal of *x(t)* with values in time-domain.

Because the analytic signal is a complex time series, envelope can be obtained from this by adding the magnitude of analytic signal over the original time domain signal *x(t)*.

In this way, for more accuracy, the frequency of impacts can thus be extracted by taking FFT or PSD of the signal envelope.

## 3. SIMULATION RESULTS

In some applications like mechanical systems cases, it's common to control a system using acceleration signal as the input. In this regard, the example of diagnosing rolling element bearing faults based on acceleration signals is carried out using the *Predictive Maintenance Toolbox* in Matlab, where the codes for the algorithms are provided and can be easily modified for the applications [12,15]. Thus, the characteristics of the excitation signal (acceleration) are defined by referring to Figure 5. In the simulated scenario, a vibration with a frequency of 2 kHz and a duration of 1.6 milliseconds is assumed to occur with each rotation of a bearing shaft. This impact is modeled as a periodic pulse train, meaning it's a repeating pattern of these short, sharp vibrations.

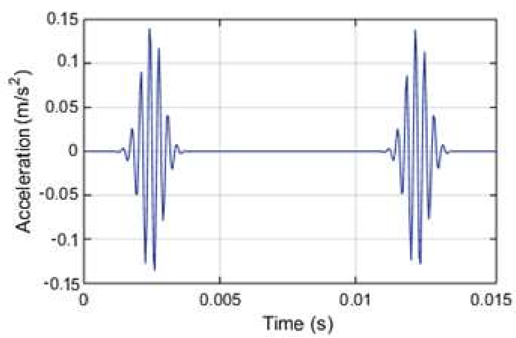


Fig. 5 The excitation signal because of bearing wear

After, the signal analysis was implemented also with Matlab, because this software offers a multitude of functions (e.g., fft, periodogram, etc.) providing specific blocks (e.g., Spectrum Estimator, Spectrum Analyzer, etc.) for PSD estimation (which we will use). The system response to the operation of a bearing with wear on the inner race, is illustrated in figure 6 (after envelopes acquired and PSD signals processing).

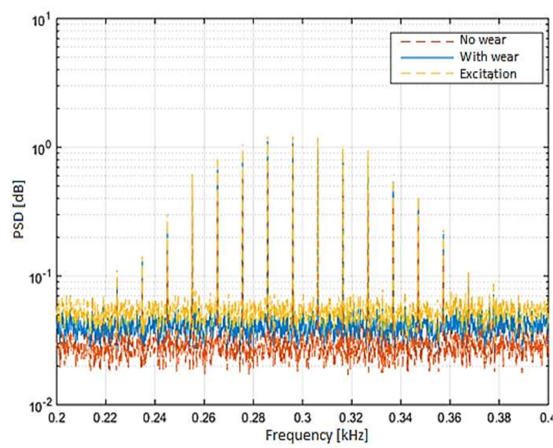


Fig. 6 Comparative diagram between the acceleration PSD signals resulting from the two working cases: without wear (red color) and with bearing wear (blue color). Representation on a logarithmic scale

A comparative diagram of acceleration Power Spectral Density (PSD) signals, with and without bearing wear, shows distinct differences in the frequency spectrum, especially when plotted on a logarithmic scale [16, 17].

Thus, the PSD of healthy bearing exhibits a relatively smooth curve with lower magnitudes, concentrated around certain characteristic frequencies of this piece. In addition, the signal presents a few prominent peaks at specific frequencies, corresponding to the rotational speed and its harmonics.

The PSD of wear bearing signal shows a more irregular and higher magnitude curve, with new frequency components, and existing peaks were broadened or shifted due to the altered vibration characteristics caused by wear. The PSD with bearing wear is expected to have a higher magnitude and broader distribution across frequencies compared to the clean signal. This is because wear introduces additional vibration components at various frequencies.

It is observed that the spectrum of defective bearing relives energy concentration and large peaks in high frequency range (greater than 0,2 kHz) when the impacts excite various structural resonances of the bearing. In this way, the energy distribution spreads across a wider range of frequencies and the increased noise level or background vibration level are higher compared to the healthy bearing case.

A bearing wear diagnosis in the early stage 4 phase (as is the case of the bearing analyzed) indicates that the bearing is nearing the end of its service life and is close to complete failure. At this stage, it is crucial to replace the bearing to prevent significant failure.

## 4. CONCLUSIONS

This paper addresses an engineering topic regarding the effects of bearing wear commonly used in constructive configuration of mechanical systems. The results highlighted that the PSD of acceleration signals changes significantly when a bearing experiences wear.

In engineering practice, PSD analysis is widely used to detect and diagnose wear of bearings in mechanical systems. Thus, changes in the shape and amplitude of PSD, in this case the appearance of high-frequency harmonics and specific frequency peaks, are aspects that indicate the presence and severity of wear.

In addition, the logarithmic scale shows differences in the magnitude of the PSD at different frequency ranges, making it easier to visualize the impact of wear on the overall vibration characteristics.

In conclusion, combining the PSD algorithm with the envelope analysis of the monitored signal proves to be a very effective signal processing technique applicable in vibration monitoring and, in the particular case of this paper, in diagnosing rolling bearing faults.

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