# Wavelet Transform Application For Detection of Bearing Fault

Erol Uyar, Burak Yeşilyurt and Musa Alci



June 24, 2018

# Wavelet Transform Application For Detection of Bearing Fault

*Erol Uyar[1], Burak Yeşilyurt[2], Musa Alcı[3]*

*[1]Elektrik-Elektronik Mühendisliği Bölümü*
*Ege Üniversitesi, İzmir*
erol.uyar@deu.edu.tr

*[2]Elektrik-Elektronik Mühendisliği Bölümü*
*Ege Üniversitesi, İzmir*
yesilyurtburak.864@gmail.com

*[3]Elektrik-Elektronik Mühendisliği Bölümü*
*Ege Üniversitesi, İzmir*
musa.alci@ege.edu.tr

## Abstract

This paper presents the application of the Wavelet transform for detection of bearing fault. Previously collected signal data is used to analyze the process. [6] The intended fault is created artificially on outer ring of cylindrical roller bearing. The vibration data is collected while bearing was rotating at a certain speed and under balance. Various signal processing techniques like time and frequency domain analysis, Fourier transform, Wavelet transform, Envelope analysis are applied on vibration data. Then after the evaluated results for healthy and faulty bearings are compared for detection the existence of fault and its location. Very accurate and concrete results are obtained successfully.

Keywords: Wavelet, transform, bearing, Fourier transform, signal processing, Envelope Analysis

## 1. Introduction

*Rotating machines make life a great deal easier and are used in many places in everyday life. Especially in industrial applications, revolving machines have an indispensable place. Roller bearings are extremely important machine parts found in all machines that have rotational motion due to their minimized power loss while providing rolling friction instead of slip friction in mechanical and electrical assemblies*

*The bearings are one of the machine parts with a high error rate and these faults can occur in various forms. As a result of defects in the roller bearings, the machines can be faulty or completely dismantled. If possible failures can not be avoided in time, loss of production is inevitable.*

*If possible faults can not be prevented in time, it is inevitable that losses will be experienced in production. The condition of the bearings must be monitored since it is necessary for the machine to operate smoothly in order to prevent such negativity. When the bearings begin to fail, these reactions are oscillating as the machine vibrates*

*For this reason, vibration analysis methods are often used to detect bearing failures. Various signal processing methods have been proposed for these error analyzes. [1, 2] Faults of the same kind that occur in the rolling bearings cause more damage to the machine than the damage of a single fault. Therefore, the diagnosis of the same type of mistakes is very important*

*Each error that occurs in the bearing is seen in its characteristic frequency when it is examined in the power spectrum. The magnitude of this characteristic frequency error in the power spectrum allows us to have information about the error rate in the bearing. When the same type of error occurs in the bearing, the characteristic error frequency is the same as if there is only one error in the bearing, but the severity of the error is different. The special cases of two identical errors occurred in the rolling bearings. [3]*

*If the error is repeated periodically, the periodic structure of the signal can be determined by a capstorm analysis. However, the power envelope analysis and the power spectrum of many machine parts, such as gearboxes, have yielded more accurate and better results in this type of systems because of the complexity of the envelope analysis. [4] Wavelet Transform (WT) and Envelope Analysis are frequently used methods for error diagnosis of bearings. [5]*

*The effect of the imbalance on the bearing for unbalanced load bearing was investigated by the short-time Fourier transform. [6] A practical application and flow chart for predictive maintenance in order to be able to detect errors in ball bearings and sliding bearings has been investigated. Using time and frequency-based data analysis methods and statistical results, mistakes can be identified for ball and roller bearings. Errors can be diagnosed incompletely thanks to the development of condition monitoring applications and predictive maintenance. [7] The effective value (RMS), peak value and crest factor results of the vibration from the roller bear important information about the condition of the roller. Spectrum comparisons can be made for faults detected in the system and Zoom and Capstrum analysis can be used to find the cause of the increased vibration [8].*

***2. Wavelet Transform (WT)***

*If the frequency content of the signal does not change with time, these types of signals are called stationary signals. The Fourier transform transforms the time-domain signal into a frequency plane and allows frequency analysis. Fourier transformation is sufficient to examine the frequency content of stationary signals. However, it has been observed that it is necessary to use transformations in which time and frequency information are displayed at the same time for the signals whose frequency content varies with time, and in which case A short-time Fourier transform (STFT) or Wavelet Transform (WT) can be used when the frequency information of the signal varies with time (non-stationary signal, for example, vibrations from a roller bearing a local fault or gear box) Fourier transformation does not indicate at what time zone these frequencies occur when we show frequency information. In short-time Fourier transform and Wavelet transform, the time and frequency information of the signal are displayed at the same time. The wavelet is a wave form with a mean time value of zero and is expressed by the following equation.*

.

$$\int_{-\infty}^{\infty} \psi(t)dt = 0 \quad (2.1)$$

Wavelet transform can be applied both in time domain and frequency domain. When applied in the transformation time plane, the convolution process is defined. In order to simplify the process, the transformation can be expressed by a simple multiplication operation as follows when the transformation is applied in the frequency domain. [11th]

*ψ (t) is the main wavelet and the following condition is satisfied*

$$\int_{0}^{\infty} \frac{|\hat{\psi}(w)|}{w} dw < +\infty \quad (2.2)$$

*ψ (w) is the Fourier transform of the main wave.*

*In short-time Fourier transform, the time-frequency resolution of the main wavelet transforms the wavelet transform when a window function is operated with a fixed resolution. Therefore, the main wavelet functions in wavelet transform fulfill the task of window functions in STFT. Therefore, when wavelet transform is applied, time-frequency resolutions change in high-frequency regions and low-frequency regions. In high frequency regions, the frequency resolution is getting worse although the time resolution is increased; while in the low frequency regions the frequency resolution increases but the time resolution deteriorates.*

### .1 Continuous Wavelet Transform (CWT)

*The analysis function is wavelet in continuous wavelet transform. The scale value of the analysis function may vary for different regions of the signal to be transformed. The continuous wavelet transform of the x (t) signal can be described as the inner product of the x (t) signal and the ψ (t) wavelet function. The continuous wavelet transform, defined for the scale factor a> 0,*

### 2.1 Continuous Wavelet Transform (CWT)

*The analysis function is wavelet in continuous wavelet transform. The scale value of the analysis function may vary for different regions of the signal to be transformed. The continuous wavelet transform of the x (t) signal can be described as the inner product of the x (t) signal and the ψ (t) wavelet function. The continuous wavelet transform, defined for the scale factor a> 0,*

$$CWT(a,b;x(t),\psi(t))= \int_{-\infty}^{\infty} x(t)\, \psi_{a,b}^{*}(t)\, dt$$

*[11,12] where ψ_ (a, b) (t) is the vector of the position and scale information of the main wavelet function ψ (t) and can be expressed as follows.*

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \quad (2.1.2)$$

*Here, the * symbol indicates the complex conjugate, while the variables a and b are known as the scale factor and the scrolling parameter. The scale factor is inversely proportional to frequency. In other words, as the scale factor becomes smaller, the wavelet is compressed, fast changing details are better captured and high frequency regions are better analyzed; As the scale factor grows, the wavelet is expanded, slowly changing details are better captured and low frequency regions are better analyzed.*

*Wavelet transform can be applied both in time domain and frequency domain. When applied in the transformation time plane, the convolution process is defined. In order to simplify the process, the transformation can be expressed by a simple multiplication operation as follows when the transformation is applied in the frequency domain. [11th]*

$$CWT\big(a,b;x(f),\psi(f)\big) = \sqrt{a}F^{-1}\{X(f)\psi^{*}(af)\} \quad (2.1.3)$$

The functions X (f) and ψ (f) are the Fourier transforms of the signals x (t) and ψ (t) respectively and F (-1) expresses the inverse Fourier transform process. The fast calculation of the continuous wavelet transform depends on the octave band analysis in which every octave is divided into equal vowels. [9] The number of octaves used in wavelet computation is determined by the time that the data is recorded. When the number of voices is determined, the desired frequency resolution of the conversion is important, and as the number of voices increases, the frequency resolution increases. [10]

*Mathematically, the wavelet transform provides flexibility in the choice of the analysis function. The Morlet Worm was used in this study because it is easy to understand because it is closely related to Fourier analysis. The Morlet wavelet is expressed in the time and frequency plane as follows.*

$$\psi(t) = e^{j2\pi f_0 t} e^{-\frac{t^2}{2}} \quad (2.1.4)$$

$$\psi(f) = \sqrt{2}\pi e^{-2\pi^2 (f-f_0)^2} \quad (2.1.5)$$

*f_0 represents the wavelet center frequency or oscillation frequency and t∈□. Selecting the wavelet center frequency to provide the f_0> 0.875 Hz condition makes the Morlet wavelet practically usable. [11,12] The real and imaginary parts of the Morlet wave are shown below.*

.

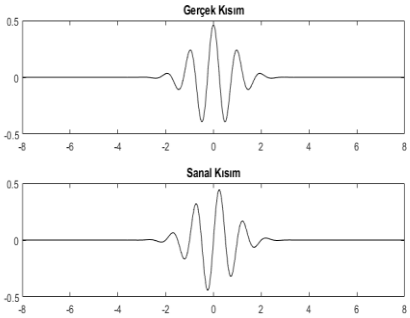


**Figure 1: The complex worthy Morlet Worm [13]**

*If you want to do phase analysis with amplitude, you can use complex Morlet wavelets*

### *3. Bearing Characteristic Frequencies*

*There are 4 types of local fault characteristic frequencies for bearings: BPFO, BPFI, BPF, FTF. The BPF (Ball Pass Frequency of Outer Ring) is the frequency of the error characteristic of the vibration generated by the rolling elements when passing over the outer ring, the frequency of the vibration generated by the rolling elements passing through the inner ring of the BPFI (Ball Pass Frequency of Inner Ring) The error characteristic frequency of the vibration occurring when rotating around its axis represents the characteristic error frequency that occurs in the result of the movement of the cage between the rings in the FTF (Fundamental Train Frequency) bearing. Based on this information, the characteristic error frequencies calculated according to the measured values in the table are as follows.*

$$\mathrm{BPFO} = \frac{\mathrm{n}}{2}\mathrm{f_r}\left(1 - \frac{\mathrm{BD}}{\mathrm{PD}}\cos\alpha\right) \tag{3.1}$$

$$BPFI = \frac{n}{2}f_r\left(1 + \frac{BD}{PD}cos\alpha\right) \tag{3.2}$$

$$BSF = \frac{PD}{BD}f_r\left(1 - \left(\frac{BD}{PD}cos\alpha\right)^2\right) \tag{3.3}$$

$$FTF = \frac{f_r}{2}\left(1 - \frac{BD}{PD}cos\alpha\right) \tag{3.4}$$

*As a result of these operations, BPFO = 87.23 Hz, BPFI = 129.44 Hz, BSF = 82.31 Hz, FTF = 6.71 Hz.*
*In this study, the dimensions and parameter values of the cylindrical roller bearing FAG brand N205-E-TVP2 are used. The parameter values of the bearing used in the calculation of the characteristic error frequencies are as follows:*
*The inner diameter of the roller is d = 25 mm,*
*Bearing outer diameter D = 52 mm,*
*Rolling element diameter BD = 7.5 mm,*
*Average diameter of rolling path PD = 38.5 mm,*
*Number of rolling elements n = 13,*
*Shaft rotation speed (revolutions) nr = 1000 rpm,*
*Spindle frequency fr = 16.67 Hz,*
*Rolling element contact angle α = 0 degree*

### *4. Creation of the Experiment Plan and Collection of the Data*

*spooled cylindrical roller bearings. For this study, the test setup was set up and data was collected from the bearing without error when the shaft bearing speed The experiment uses N205-E-TVP2 coded FAG of the roller was running at 1000 rpm. Thereafter, on the rolling path of the outer bracelet of the roller, a diamond-tipped lathe pen was used to create an error of 0.05 mm in depth and 7.5 mm in length, and the data were collected while the shaft was rotating at a speed of 1000 rpm. The data taken from the bearing were recorded on the computer with the aid of an accelerometer. The Dytran 3200B6 shock absorber is used in the vibration tests of the bearings. In the experimental phase of this work, a two-channel dynamic signal amplification unit named DBK4, which was produced by IOtech firm, was used in order to strengthen the dynamometer signals. The A / D converter (DAQBOARD 2000) produced by IOTECH Inc 'was used to convert the analog signals obtained during the experiments into digital. The data were collected with a sampling frequency of 20kHz for 25 seconds. [6]*

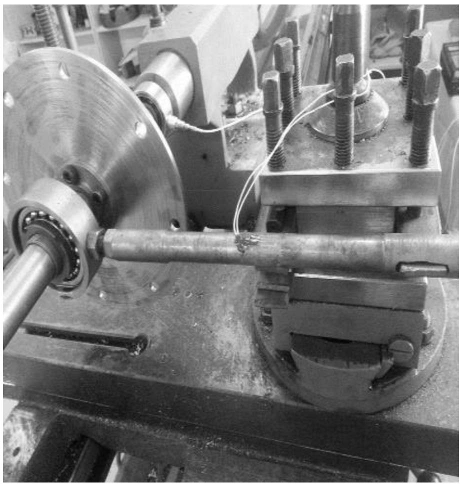

**Figure 2: Bearing Test Setup [6]**

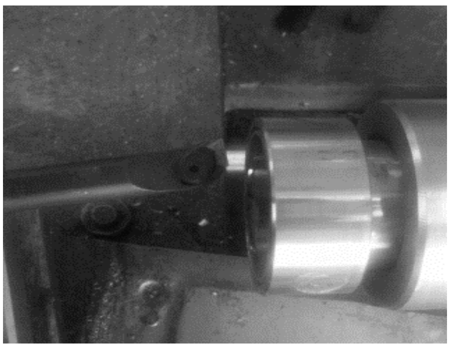

**Figure 3: Creation of Artificial Error on the Outer Ring Rolling Path of Test Roller [6]**

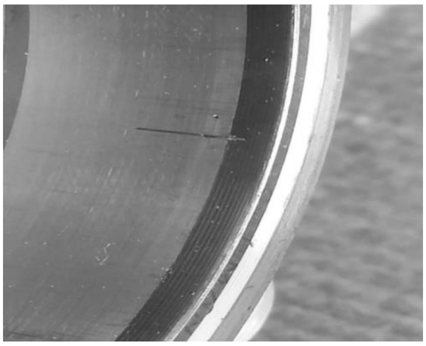

**Figure 4: Local error applied on outer ring raceway [6]**

**Figure 5: Transfer of Collected Data to Computer Environment [6]**

## *5. Experimental Results*

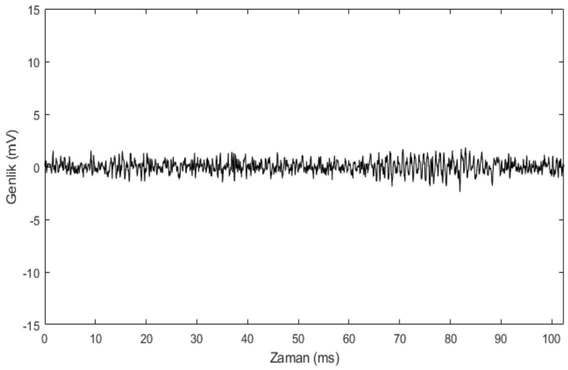


**Figure 6: Time Base of Healthy Bearing Vibration Signal**

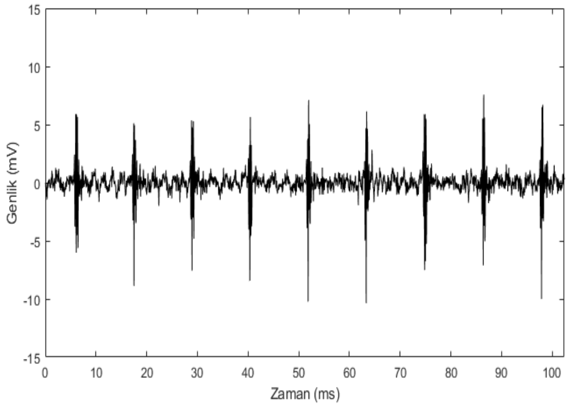


**Figure 7: Time-based representation of faulty bearing vibration signal**

*The time-axis representation of rolling-out data is shown in Figure 6 and Figure 7. The time axis is approximated (102.4 milliseconds). While the collected data from the healthy bearing does not show any change over time, the data collected from the bearing bearing the error contains periodic repetitive pulses due to error. Periodically, the impact of the resulting impacts gives us an idea of the local error of the error in the bearing. By looking at the signals given in the time domain, it can be clearly seen which one is healthy and which is wrong. As a matter of fact, it is not possible to determine in which region of the bearing the error is by comparing only the representations in the time plane.*

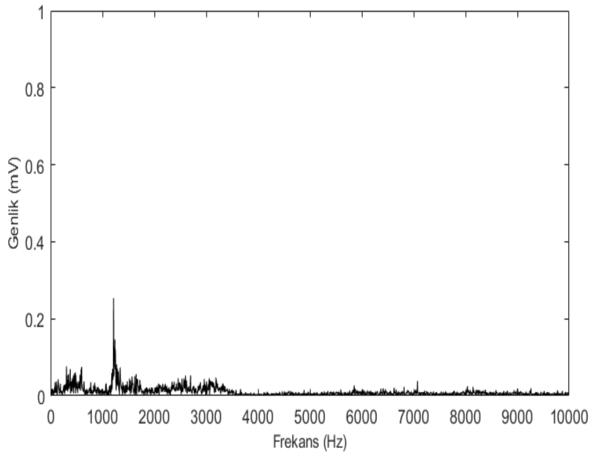


**Figure 8: Frequency Plane Display of Healthy Bearing Vibration Signal**

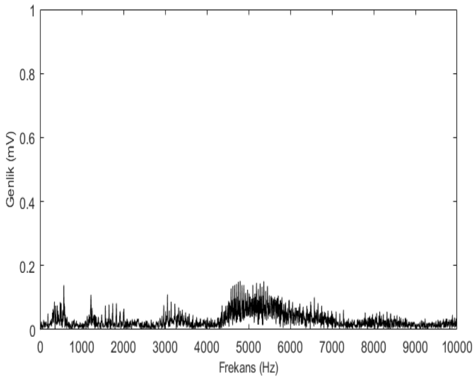


**Figure 9: Frequency Plan of Imperfect Bearing Vibration SignalDüzleminde Gösterimi**

*The representation of the collected data on the frequency plane with the help of the Fourier transform is shown in Figure 8 and Figure 9. When the error signal is examined in the frequency domain, it is seen that the system enters the resonance around 5 kHz. However, in which region of the bearing the error occurred, the results of the Fourier transformation shown above are still compared and can not be said clearly*

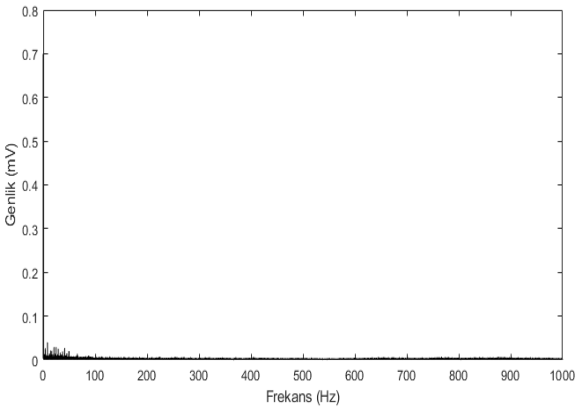


**Figure 10: Envelope Spread of Healthy Bearing Vibration Signal**

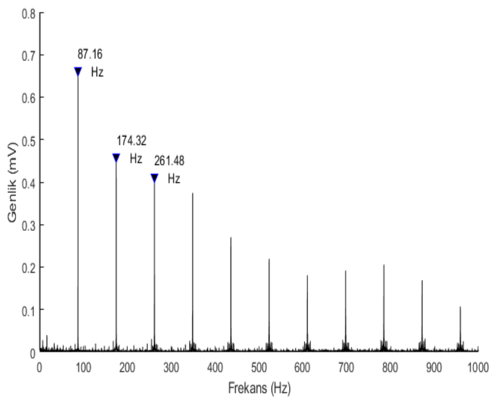


**Figure 11: Envelope Spectrum of Incorrect Bearing Vibration Signal**

*The envelope spectrum (up to 1 kHz) of the harvested data is shown in Figure 10 and Figure 11. When the envelope spectra are compared, the harmonics are not observed in the healthy bearing, and the faulty bearing shows harmonics at the characteristic error frequency of 87.16 kHz and at the exact multiple of this frequency value.*

.

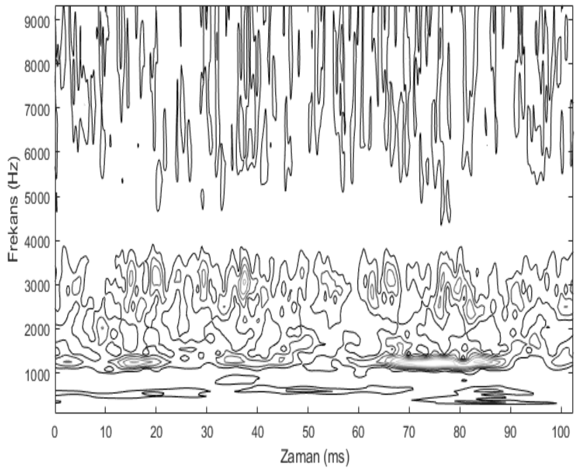


**Figure 12: Wavelet Transform of Healthy Bearing Vibration Signal**

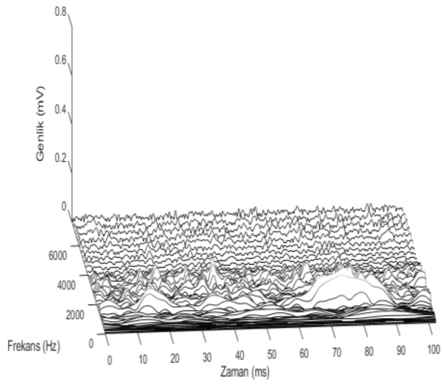


**Figure 13: Wavelet Transform of Healthy Bearing Vibration Signal**

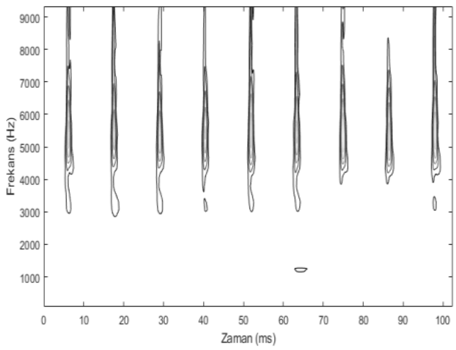


**Figure 14: Wavelet Transform of the Incorrect Bearing Vibration Signa**

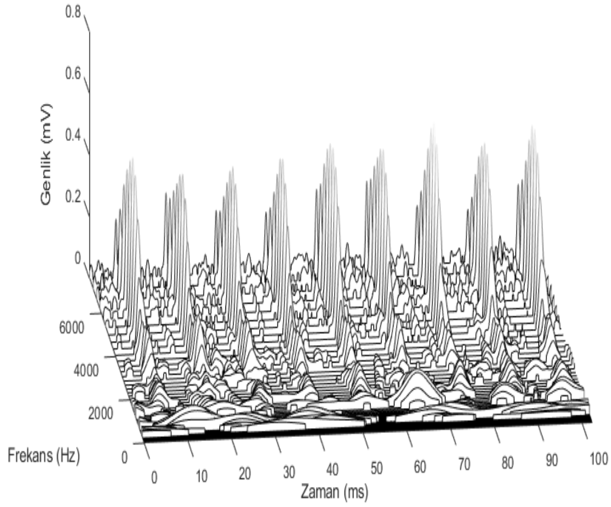


**Figure 15: Wavelet Transform of the Inclined Bearing Vibration Signal**

*The result of the wavelet transformation of the data collected from the healthy bearing is shown in Figure 12 and Figure 13. The result of the wavelet transformation of the data collected from the bearing with error is shown in Fig. 14 and Fig. When the results of wavelet transform of healthy and erroneous data are examined; it is seen that the system of the harmonics having the fundamental frequency of 87.32 Hz caused these effects to resonate around 5 kHz due to these harmonics which occurred in the system during the repetition period of the erroneous period in which the ball bearing the error forms a time period of 11.46 milliseconds*.

***6. Conclusions***

*Since the frequency content of the vibration signals recorded at the local fault bearing changes with time, the Fourier transform alone is not enough to interpret the error characteristic. For this reason, it was decided to use Wavelet transform in this study. Time and frequency information can be shown at the same time due to the wavelet transform applied to the signal. The time intervals at which the vibration pulsations created during the operation of the failed roller occurred were found to be 11.46 milliseconds. With reference to these time intervals, the fundamental frequency of the harmonics generated by the harmful effects in the system is calculated as 87.32 Hz. It has been determined that the error is due to the periodic repetition of the error events and that the error is a local error, after which the Wavelet Transform and the Envelope Spectrum results are in agreement with each other and with the BPFO given by the calculated characteristic error frequencies (3.1).*

## References


[1] R. B. Randall, and J. Antoni, "Rolling element bearing diagnostics – A tutorial," Mechanical Systems and Signal Processing, Vol.25, No.2, 2011, pp.485-520.

[2] N. Tandon, and A. Choudhury, "A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings," Tribology International, Vol.32, No.8, 1999, pp. 469-480

[3] Bao, M., and Zhao, C., "Recognition of Bearing Faults of The Same Kind," ASME Paper DE-Vol. 38, 1991.

[4] Wan, X., and Zhao, C., "The Extraction of The Fault Signature of Gearboxes Using Optimum Complex Envelope Spectrum," ASME Paper DE-Vol. 38, 1991.

[5] Rubini R, Meneghetti U. Application of the envelope and wavelet transform analyses for the diagnosis of incipient faults in ball bearings[J]. Mechanical systems and signal processing, 2001, 15(2): 287-302.

[6] Yesilyurt, I., Ozdemir O., "Dengesiz Yüke Maruz Silindirik Masuralı Rulman Arızasının Kısa Zamanlı Fourier Dönüşümü Yardımıyla Belirlenmesi", Uluslararası Katılımlı 17. Makina Teorisi Sempozyumu, İzmir, 2015.

[7] Koizumi, T., and Kiso, M., and Taniguchi, R., "Preventive Maintenance for Roller and Journal Bearings of Induction Motor Based on the Diagnostic Signature Analysis," ASME Paper No. 85-DET-41, 1985.

[8] Brown, D.N., and Jensen, T., "The Use of Crest Factor and Cepstrum Analysis for Bearing Fault Detection-A Case Study from Kénogami Paper Mill, Quebec, Canada," Application Notes.

[9] Yesilyurt, I., "Gearbox fault detection and severity assessment using vibration analysis, PhD Thesis," University of Manchester-UK, 1997.

[10] Yesilyurt, I., Ozturk, H., "Tool Condition Monitoring in Milling Using Vibration Analysis," 2007

[11] Chui, Ch. K., *An Introduction to Wavelets: Wavelet Analysis and its Applications-Vol. I* (Academic Press, Boston), 1992.

[12] Meyer, Y., *Wavelets: Algorithms & Applications* (Society for Industrial and Applied Mathematics, Philadelphia), 1993.

[13]https://www.mathworks.com/help/wavelet/ref/morlet.html