Study Of Bearing Rolling Element Defect Using Emperical Mode Decomposition Technique

Purnima Trivedi, Dr. P K Bharti
Mechanical Department
Integral university

Abstract— **Bearing failure is one of the major causes of breakdown in rotating machinery. Failure of bearings can results in costly downtime. Therefore condition monitoring of bearings plays an important role in machine maintenance. In condition monitoring the observed signal is often corrupted by noise during the transmission system. It is important to detect the elementary fault in advance before failure occurs. Therefore it is important to understand the behavior of the occurrence of faults and condition monitoring of the bearings. Among the various methods available for diagnosis and condition monitoring of bearing elements, vibration measurement is the most common one. The present study is focused on the fault diagnosis of taper roller bearings (NBC Bearing number: 30205). The experimental study has been made for the analysis of groove defect on the roller. Width and depth of the defect were approximately 1.40 mm and 0.30 mm respectively and were throughout the length of the roller. These defects were produced by using the Electric Discharge Machining (EDM). The present research work involves the application of Empirical Mode Decomposition (EMD) technique along with the envelope for the analysis of groove defect on the rollers. EMD is adaptive signal decomposition method, which is able to decompose non-linear and non-stationary data into a sequence of amplitude modulation/ frequency modulation (AM/FM) components or a like. These independent components to be obtained are called intrinsic mode functions (IMFs). The selection of appropriate IMFs is also done in order to extract the exact location of defects on the rollers. The selection of the IMF is based on the maximum kurtosis criteria. Kurtosis reveals the occurrence of defects in rotating machinery. For the normal bearing kurtosis is near about 3 and bearing with considerable defect have higher value of kurtosis. Thus kurtosis can be taken as the selection criteria for the selection of IMF. Therefore IMF with maximum kurtosis was selected for the analysis of defects in the rollers.**

The proposed method is also compared with the traditional FFT which was directly applied to the raw signal of the faulty bearing. By comparison, between the proposed method and FFT, it is concluded that, the EMD method gives better result as well as defects can be easily identified by EMD. Whereas, it is difficult to identify defects by FFT. The results obtained by the proposed method are very close to the theoretical values of the defects. The roller defect frequency, for single roller groove deviate 2.1 % from the theoretical value of the roller defect frequency.

Keywords---- Fast Fourier Transformation (FFT), Empirical Mode Decomposition (EMD), Intrinsic Mode Functions (IMFs), Kurtosis, Electric Discharge Machining (EDM), Condition Monitoring, Envelope detection, Hidden Markov Models, Artificial Neural Network, Ball pass frequency inner race (BPFI), Discrete wavelet transforms (DWT), Crest factor.

1. INTRODUCTION

1.1 Background: A bearing is a machine element which supports other moving machine elements. It permits relative motion between the contact surfaces of the machine elements. Rolling element bearing is vital component for power transmitting systems within the machine tools. Rolling element bearings are used today in the design of increasingly complex arrangements, such as high speed, and high temperature, heavy loadings and requiring continuous operations. A clear understanding of vibrations associated with them is highly needed. There is also a growing tendency that many rotating machines supported by the rolling element bearings are now being designed for working at high speed.

1.2 Different condition monitoring techniques for bearings: Condition monitoring is a field of technical activity in which selected parameters associated with the machinery operation is observed for determining integrity. Condition monitoring is essential for the maintenance management of the industry, which usually involves five distinct phases such as detection of fault, diagnosis of fault, prognosis of fault progression, prescription for treatment of a problem and post mortem. Generally, there are four main indicators to determine bearing condition; oil or particle analysis, temperature, mechanical vibration and acoustic vibration

1.2.1 Vibration analysis: Vibration produced by rolling bearings can be complex and can result from geometrical imperfections during the manufacturing process, defects on the rolling surfaces or geometrical errors in associated components. Noise and vibration is becoming more critical in all types of equipment since it is often perceived to be synonymous with quality and often used for predictive maintenance. Vibration condition monitoring is popular for its versatility and its effectiveness. Meanwhile, vibration in machines causes periodic stresses in machine parts, which lead to fatigue failure. Vibration of machines is a parameter, which often indirectly represents the health of machines and is generally capable of detecting more kinds of machine faults when compared with the other techniques. Vibration monitoring also has advantages as a non-destructive, clean, relatively simple and cost effective technique [Hale, V. et al.1995]. Vibration monitoring of rolling element bearings are typically conducted using a case mounted transducer: an accelerometer, velocity pickup, and sometimes a displacement sensor. Acceleration signals, obtained from case mounted sensors, emphasize high frequency sources, while displacement signals emphasize lower frequency sources, with velocity signals falling between the extremes. There is a large amount of information contained in the vibration signals that are obtained by monitoring at the various key points of a machine [Chen and Mo, 2004]. Every machine in standard condition has a certain vibration signature and when fault initiates or develops in them its signature changes. The increased level of vibration and introduction of additional peaks in signal is an indication of defect [Friswell M. et al. 2010].

1.2.2 Frequency domain analysis: Spectral analysis of vibration signal is widely used in bearing diagnostics. It was found that frequency domain methods are generally more sensitive and reliable than time domain methods. The advent of modern Fast Fourier Transform (FFT) analyzers has made the job of obtaining narrowband spectra easier and more efficient. In [Alfredson R. J. et al. 1985] it was demonstrated that the spectrum of the monitored signal changes when faults occur. In [Tandon N. et al. 1999] a bearing mathematical model incorporating: the effect of the bearing geometry, shaft speed, bearing load distribution, types of loads (both radial and axial), the shape of the generated pulses, transfer function of the path and the exponential decay of vibration due to the damping property of the bearing was designed. This technique is very accurate if the rpm of the shaft does not change over time or does not change at least during each updated duration of time analysis [Igarashi, T. et al. 1982].

In [Brown D. N. 1989] it was reported that defects on rolling elements can generate a ball spin frequency (BSF) or some multiple of it. It was shown that the spectrum can be either a narrow band single spike or a series of narrow band spikes spaced at BSF or FTF. In [Taylor J. I. 1980] it was shown that when more than one ball defects was present, sums of BSF were generated. The BSF could be generated if the cage is broken at rivet. Defects on the balls are often accompanied by a defective inner race and/or outer race defect. In [Smith J. D. et al. 1984] it was reported that spectral analysis of bearings with multiple defects on different components is usually complex.

Frequencies generated in different defective components will add and subtract, therefore some spectrum will contain more than one of the basic frequencies i.e., BPFO, BPFI, BPFB, FTF. In some cases the harmonics of basic frequencies i.e., lx, 2x, 3x, etc., can be identified in the spectrum. In [Osugawu C. et al. 1982], one reason for the absence of defect frequencies in the direct spectrum was found to be due to the averaging and shift effect produced by the variation of the impact period and intermodulation effect.

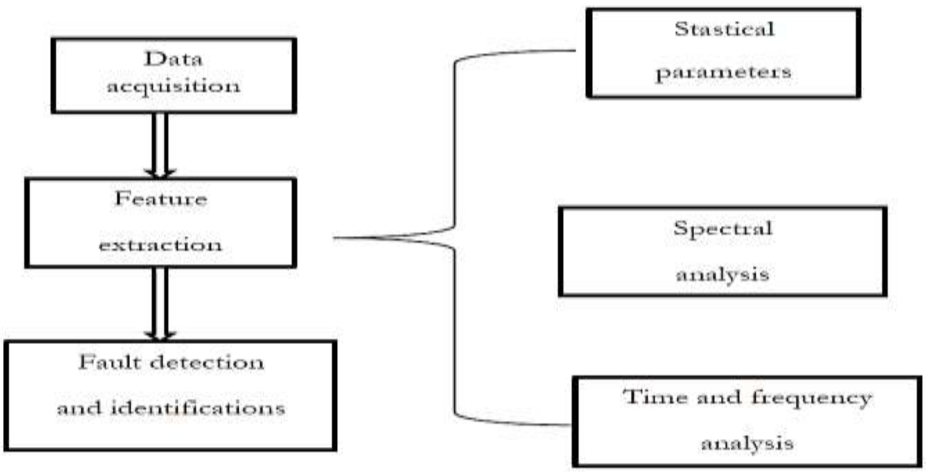


Figure 1. General vibration fault diagnosis procedure

1.2.3 Time domain analysis: The Measurement of signal energy can be a good indicator of a bearing's health. In time domain analysis the vibration signal are represented in amplitude and time. Statistical parameters (RMS, Kurtosis, Crest factor and Skewness) are normally used for fault detection in time domain analysis. The overall root-mean-square (RMS) of a signal is a representative of the energy. This method has been applied with limited success for the detection of localized defects [Miyachi T. et al. 1986]. However it is expected that high value of RMS corresponds to an overall deterioration of the machine. However, in some cases this criterion had limited success [Tandon N. et al. 1993]. The crest factor is a modified quantity of RMS and is defined as a ratio of the maximum peak of the signal to its RMS value. The value of the crest factor can be regarded as a feature for condition monitoring or fault diagnosis. In [Mathew J. et al. 1984] it was shown that crest factor can be used as an alternative measurement instead of RMS level of vibration. It was found that crest factor can be used in fault detection rolling element bearing with limited access. The fourth moment, normalized with respect to the fourth power of standard deviation is quite useful in fault diagnosis. This quantity is called kurtosis. Kurtosis is a compromise measure between the insensitive lower moments and the over-sensitive higher moments. It was reported that the kurtosis can be a good criterion to distinguish between a damaged and a healthy bearing [Heng R.B.W et al. 1998]. It was reported in [Williams T. et al. 2001] that a healthy bearing with Gaussian distribution will have a kurtosis value about 3. When the bearing deteriorates this value goes up to indicate a damaged condition. The value reduces again when the defect is well advanced. Therefore, this is most effective in identifying impending failure, when the kurtosis significantly exceeds a value of 3. Typical plot of the time domain is shown in the figure 2

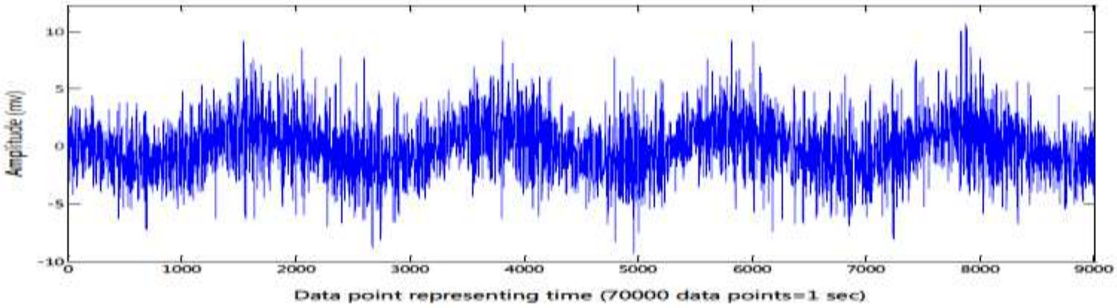


Figure 2. A typical time domain signal for defect free bearing

1.2.4 Statistical parameters: Statistical analyses of vibration signals are useful for detecting rolling elements bearing faults. It mainly includes Kurtosis, Skewness, Variance, Root Mean Square (RMS), and Crest Factor Statistics, which provides useful information for vibration analysis in fault diagnosis of bearing. Root mean square (RMS) value, crest factor, kurtosis, skewness, standard deviation, etc. are the most commonly used statistical measures used for fault diagnosis of rolling element bearings. Statistical moments like kurtosis, skewness and standard deviation are descriptors of the shape of the amplitude distribution of vibration data collected from a bearing, and have some advantages over traditional time and frequency analysis, such as its lower sensitivity to the variations of load and speed, the analysis of the condition monitoring results is easy and convenient, and no precious history of the bearing life is required for assessing the bearing condition [Kankar P. K. et al. 2011]

2 Bearing fault analysis: Each time a defect strikes its mating element, a pulse of short duration is generated that excites the resonances periodically at the characteristic frequency related to the fault location. The resonances are thus amplitude modulated at these frequencies. By demodulation at one of these frequencies the signal containing information of the fault can be obtained. Enveloping procedure can be used to demodulate the bearing signal [Mcfadden P. D. et al. 1984]. Envelope analysis is an effective method for the fault diagnosis of rolling bearings. With the traditional envelope analysis, a bearing fault can be inspected by the peak value of an envelope spectrum. For obtaining an envelope signal, a band-pass filter with an appropriate central frequency and the frequency interval needs to be decided from experimental testing which yields subjective
influences on the diagnosis results [Mcfadden P. D. et al. 2000]. Recently, a new signal analysis method called the empirical mode decomposition (EMD) has been brought out by Huang [Huang N. E. et al. 1998]. The EMD is a self-adaptive signal analysis method which is based on the local time scale of the signal and decomposes a multi-component signal into a number of intrinsic mode functions (IMFs). Each IMF represents a mono-component function versus time. The spectral band for each IMF ranges from high to low frequency and changes with the original signal itself. Therefore, the EMD is a powerful signal analysis method for treating non-linear and non-stationary signals. In applications, the EMD has been successfully applied to numerous investigation fields, such as acoustic, biological, ocean, earth-quake, climate, fault diagnosis, etc. [Huang N. E. et al. 2005]. There are several types of defects that can occur on a bearing, such as wear, cracks or pits on races or rolling elements. When a rolling element strikes to a defect on one of the races, or a defective roller strike to the races (inner race, outer race), this strike creates impulses. Since the rolling element bearing rotates, those impulses will be periodic with a certain frequency called fundamental defect frequencies.

2.1 Bearing frequency

2.1.1 Operating frequency: Operating frequency of bearing is the frequency of shaft at which shaft rotates, If the shaft is rotating at RPM, then operating frequency of bearing will be

$$f_n = \frac{s}{60} \qquad \text{(I)}$$

Where, f_n is the operating frequency in Hz.

2.1.2 Fundamental train frequency (FTF): It is also known as cage frequency and is equivalent to the angular velocity of the individual ball centers [Geramitchioski T. et al. 2011].
Suppose,
f_n = The rotating frequency of the bearing shaft(Hz),
D =Pitch circle diameter of the bearing,
d =Mean roller diameter,
β =Contact angle between inner race and outer race,
z =Number of rollers,
Then FTF/ Bearing component frequency is given by [Wang D. et al. 2009]

$$FTF = \frac{f_n}{2}\left(1 - \frac{d}{D}cos\beta\right) \qquad \text{(II)}$$

2.1.3 Ball pass frequency outer race (BPFO): The ball pass frequency of the outer race is defined as the frequency of the balls passing over a single point on the outer race. The BPFO can be described as the number of balls multiplied by the difference frequency between the cage and the outer race, can be defined as [Wang D. et al. 2009]

$$BPFO = \frac{zf_n}{2}\left(1 - \frac{d}{D}cos\beta\right) \qquad \text{(III)}$$

2.1.4 Ball pass frequency inner race (BPFI): The ball pass frequency of the inner race is defined as the frequency of the balls passing over a single point on the inner race of the bearing. Ball pass frequency of inner race (BPFI) is defined as [Wang D. et al. 2009]

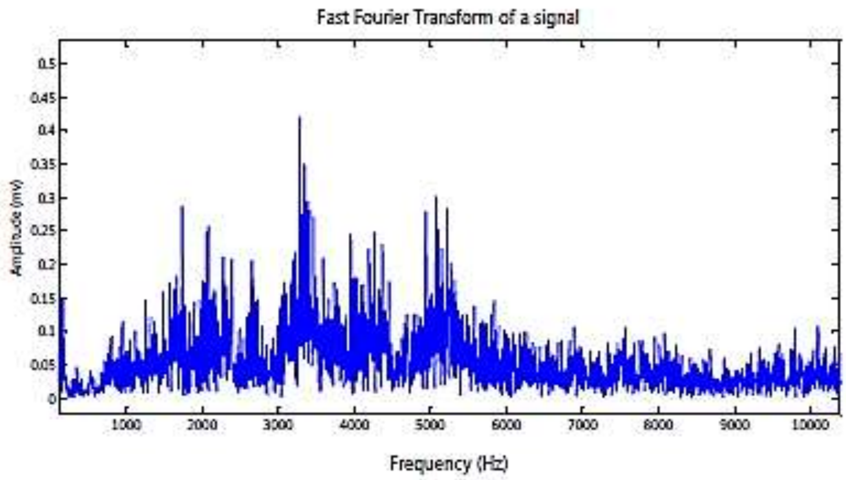
$$BPFI = \frac{zf_n}{2}\left(1 + \frac{d}{D}cos\beta\right) \qquad \text{(IV)}$$

2.1.5 Ball spin frequency (BSF): The angular velocity of a ball about its own axis is called ball spin frequency (BSF), and is given [Wang D. et al. 2009] by:

$$BSF = \frac{Df_n}{2d}\left(1 - \left(\frac{d}{D}cos\beta\right)^2\right) \qquad \text{(V)}$$

2.1.6 Defect frequency: The defect frequencies of the rolling element are the same as their rotational frequencies, expect for the BSF. If the inner race of the bearing is defective, the BPFI amplitude increases, because roller contacts the defect as they rotate around the bearings. Similarly if there is a defect in the outer race, the BPFO is excited because of the presence of defect on outer race. When one or more rollers have defects such as groove defects (Cracks), or spall (i.e. a missing chip of material from the roller), the defect impacts both the inner race and the outer race each time one revolution of the rolling element is made. Therefore the defect frequency for the roller is visible at 2 times (2× BSF) the BSF rather than the roller spin frequency [Plant Engineers Hand Book by R. Kaith Mobely (2001 edition)]. The above equations for bearing frequencies are based on the assumption of pure point/rolling contact and having no slip between the ball/rollers and races.

2.2 Fast Fourier Transform (FFT): Fourier transform is a signal processing technique that connects the time domain and frequency domain. In the early 1800‘s, a French mathematician named Joseph Fourier proved that all waveforms are composed of many individual frequencies which can broke down into their separate components mathematically. This concept is based on the Fourier Integral. However, this mathematical technique was not used extensively until the development of computers due to its computationally intensive nature. It is a method for efficient computing the discrete Fourier transform of a series of data samples (Referred to as a time series) [Cochran W. T. et al. 1967]. This tool is extremely useful for determining what dominant frequencies are present in a particular vibration. For many signals, Fourier analysis is extremely useful because the signal‘s frequency content is of great importance. So why do we need other signal processing techniques, like Empirical Mode Decomposition (EMD), and wavelet analysis etc.



Fourier … analysis has a serious … drawback. In transforming … to the frequency domain, time … information is lost. When looking at a Fourier transform of a signal, it is impossible to tell when a particular event took place.

Figure 3. Typical Fast Fourier Transform (FFT) of a signal

2.3 Detection of b… … time a defect in a rolling element be… . This impulse is of extremely short du… …y low level over a wide range of frequencies. It is this wide distribution of energy, which makes bearing defects so difficult to detect by conventional spectrum (FFT) analysis in the presence of vibration from other machine elements. Fortunately, the impact usually excites a resonance in the system at a much higher frequency than the vibration generated by the other machine elements, with the result that some of the energy is concentrated into a narrow band near bearing resonance frequency. As a result of bearing excitation repeated burst of high frequency vibrations are produced, which is more readily detected. Take for example the bearing that is developing a crack in its outer race. Each time a ball passes over the crack, it creates a high-frequency burst of vibration, with each burst lasting for a very short time. In the simple spectra of this signal one would expect a peak at BPFO instead we get high frequency haystack‘ because of excitation of bearing structural resonance. The signal produced is an amplitude-modulated signal with bearing structural resonance frequency as the carrier frequency and the modulation of amplitude is by the BCF (message signal). Envelope Detection, the technique for amplitude demodulation is always used to find out the repeated impulse type signals. The ED involves three main steps. First step is to apply a band-pass filter, which removes the large low-frequency components as well as the high frequency noise only the burst of high frequency vibrations remains as shown in Fig. 4 (b). In the second step, we trace an "envelope" around the bursts in the waveform (Fig. 4 (c)) to identify the impact events as repetitions of the same fault. In the third step, FFT of this enveloped signal is taken, to obtain a frequency spectrum. It now clearly presents the BPFO peaks (and harmonics) as shown is Fig. 4 (d).

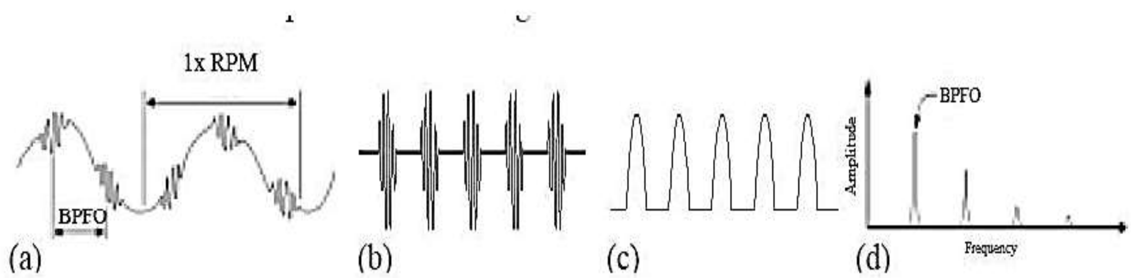


Figure 4. Envelope detection process (a) Unfiltered Time Signal (b) Band passed Time Signal (c) Envelope of Band passed Signal (d) Envelope Spectrum

The bearing structural resonance frequency is selected as the central frequency of the band-pass filter. Traditionally, impact tests are carried out on bearing to identify the resonant frequency. However, impact tests are not a necessity; the resonant frequency can be identified from inspection of the unfiltered signal‘s spectrum **[**McFadden P. D. et al. 1984**]**. There are different ways to extract the envelope; traditionally band-pass filtering, rectifying and low-pass filtering is used to carry out the demodulation.

However, Hilbert transform has also been used very effectively for ED **[**Proakis J. G.et al. 2000**]**. In present work, Hilbert Transform is used to extract the envelope.

2.3.1 Measuring a vibration signal for envelope detection: An accelerometer and a tachometer are used to measure the vibration signal and rotational speed of a rolling element bearing. Choose a sampling rate that is at least two times higher than the highest frequency component of interest. Also use the accelerometer with a high cut off frequency to cover the frequency band that the envelope detection technique uses.

2.3.2 Hilbert transform: A piece of signal $x(t)$ and its Hilbert transform $H[x(t)]$ is expressed as [Kerschen G. et al. 2009]:

$$H[x(t)] = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau}\, d\tau \qquad \text{(VI)}$$

Where $\boldsymbol{t}$ and $\boldsymbol{\tau}$ are the time and translation parameters respectively.

It is well known that the Hilbert transform is a time-domain convolution that maps one real-valued time history into another and it is also a frequency-independent 90^0 phase shifter. So, it does not influence the non-stationary characteristics of modulating signals. In actual application, modulation is usually caused by machine faults. Hence, in order to find fault related signatures, demodulation has to be done [Wang D. et al. 2009]. Fortunately, this requirement may be completed by construction of analytic signal, which is given by

$$B(t) = x(t) + iH[x(t) = b(t)e^{\phi(t)} \qquad \text{(VII)}$$

where, $b(t) = \sqrt{x^2(t) + H^2[x(t)]}$,

$$\phi = arc\ tan\ \frac{H[x(t)]}{x(t)}$$

And $i = \sqrt{-1}$, $b(t)$ is the envelope of $B(t)$.

The Fourier transform of signal $B(t)$ is notified by $B\wedge(i\omega)$and its properties are provided as [Heng R.B.W et al. 1998]:

$$B\wedge(i\omega) = \begin{cases} 2\dot{X}(i\omega), \omega \geq 0 \\ 0, \omega < 0 \end{cases} \qquad \text{(VIII)}$$

Where ω denotes the angular frequency of $B\wedge(i\omega)$ and $\dot{X}(i\omega)$ is the Fourier transform of $x(t)$

On one hand, the Hilbert transform can demodulate modulated signals and extract modulating signals. And on the other hand [Wang Dong et al. 2009] in their research observe that the spectrum analysis of an envelope signal obtained from an analytic signal is able to enhance the amplitude of an original signal by Eq. VIII, which may be useful to increase the amplitude of bearing fault signatures for visual inspection.

2.3.3 Empirical Mode Decomposition (EMD): The empirical mode decomposition is an adaptive signal decomposition method, which is able to decompose non-linear and non-stationary data into a sequence of amplitude modulation/ frequency-modulation (AM/FM) components or alike. These independent components to be obtained are called intrinsic mode functions, which must satisfy the two conditions [Huang N. E. et al. 1998]. Empirical mode decomposition procedure can be explained with the help of flow chart as described following:

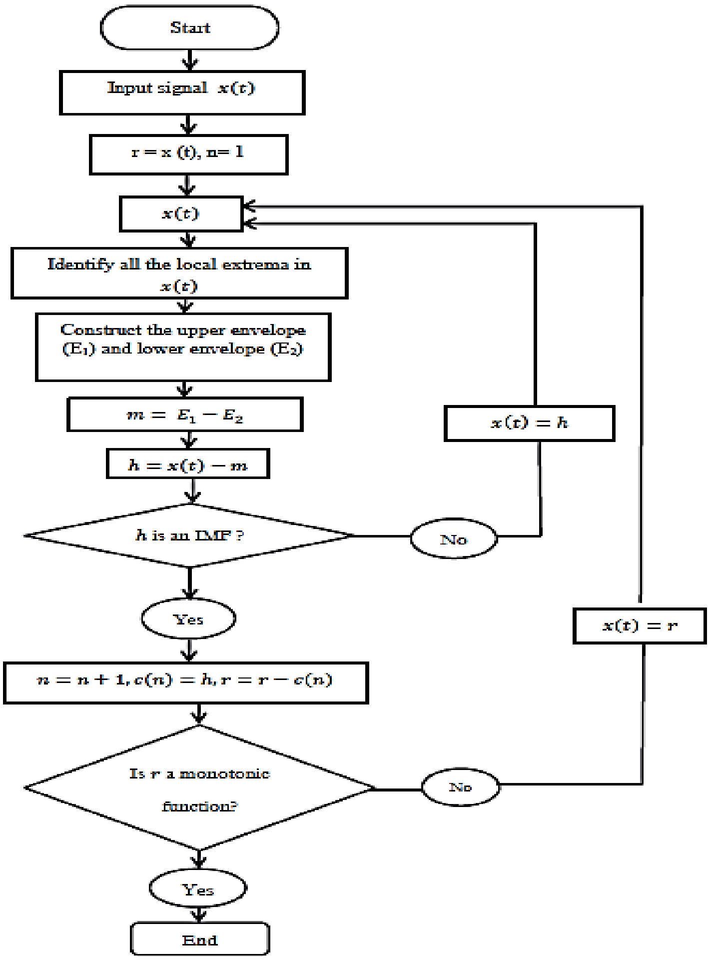


Figure 5. Procedure of empirical mode decomposition (EMD)

4. Experimental facilities and measurements:

The experimental setup consists of motor (1- phase 4-pole induction motor), two taper roller bearings, shaft, and V-belt pulley with having three speeds options. The material of shaft is mild steel.

4.1 Descriptio

Schematic of experimental setup on which experiments were conducted is shown in Figure 6.

Figure 6: Experimental set up.

Table 1. Description of experimental set up

Bearing Specification	
Bearing used	NBC-30205 (Taper roller bearing)
Inside diameter of the bearing	25 mm
Outside diameter of the bearing	52 mm
Pitch circle diameter of the bearing (D)	38.5 mm
Mean roller diameter (d)	6.39 mm
Numbers of rollers (z)	17
Motor specification :-	
Power supply	220/230 V, 4.2 A, AC power supply
Power	0.5 HP
Speed range (using pulley)	1150 rpm, 2050 rpm, 3050 rpm
Rotor shaft specification:	
Diameter of the shaft	28.5 mm.
Length of the shaft	570 mm
Distance between bearings	405.5 mm
Density of the shaft	7850 kg/m3
Elasticity of the shaft	210000 Mpa
Sensitivity of accelerometer	1000 mV/g
Sampling rate of data acquisition	70000 sample/second

In this analysis taper roller bearing (bearing number: 30205 nbc made) has been used. Geometrical configuration of the bearing is shown in the above table (Table 1). Here we had identified the defects in the rollers of the bearings. For this purpose groove defects had been produced on the roller of the bearings. The approximate width and depth of the defect was 1.40 mm and 0.3 mm respectively. Figure 6 shows the different defects on the rollers of the bearing:

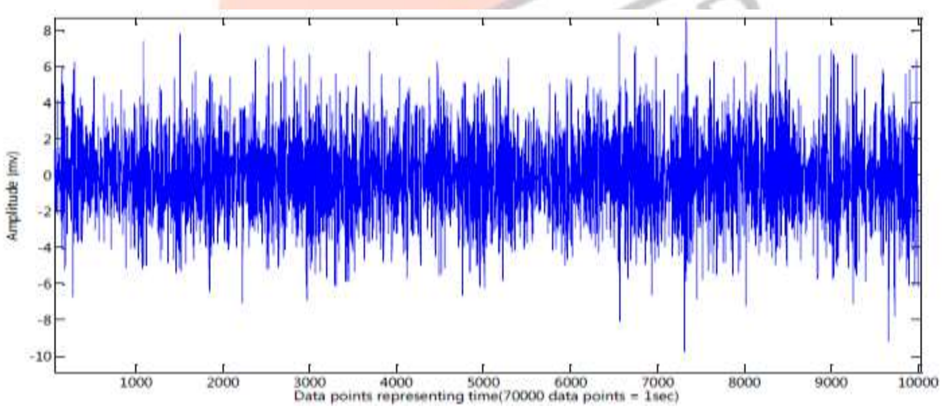
Figure 7. Roller defect at 0º

5. Result and discussion: In this work, Empirical Mode Decomposition (EMD) technique has been used for the identification of the defects in rollers of the bearings. As from the EMD, different IMFs are obtained, then after selecting the appropriate IMF, envelope spectrum (FFT) and envelop (in time domain) of selected IMF are also plotted. The result (envelope spectrum) is also compared with the traditional FFT obtained directly from the raw signal. From the analysis it is observed that it is difficult to identify the defects on the roller by traditional FFT. However it can be easily detected by EMD method. The experimental rotating frequency $'f_n'$ is 34.17 Hz and the sample rate is 70000 samples/second. The defect frequency of the roller can be calculated from equation (V) and fundamental train frequency/ cage frequency can be calculated from equation (II). In these equations the contact angle (β) of the taper roller bearings is assumed to be zero. The values of D, d are given in table 2. Theoretical bearing characteristics frequencies (BCF) for defects are shown in table 2.

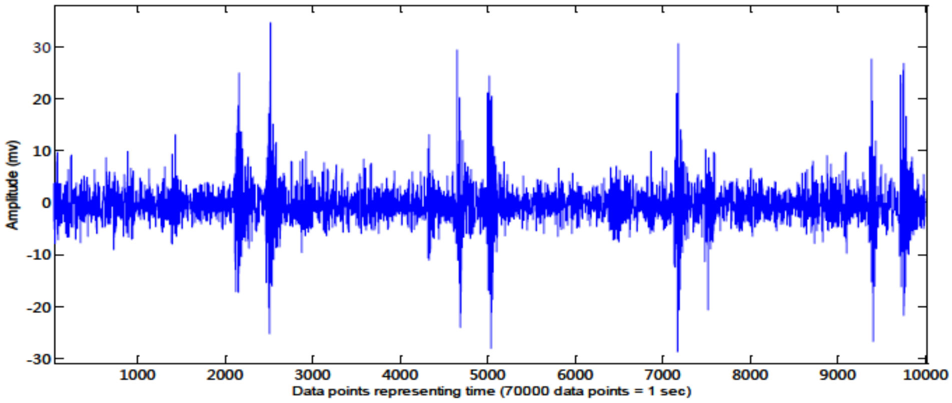
Table 2. Theoretical BCF for faults

Fault Type	Single roller groove defect (at 0º)
Roller defect frequency for f_n=34.17 Hz	200.2 Hz
Time interval of impacts	0.005 sec
Samples between impacts	350
FTF for f_n= 34.17 Hz	14.2 Hz

5.1 Identification of the single groove defect on the roller: Time domain waveform of an acceleration signal picked up from a 30205-taper rolling bearing without defect and with single groove defect of approximate width 1.4 mm and depth 0.3 mm on the roller is shown in Figure 7(a) and 7(b) respectively. No distinct impulse is observed in the raw signal of defect free bearing as shown in figure 7 (a). The amplitude of this signal lies in the range of +9 to -10 mV. The raw signal for bearing with single roller groove defect as shown in figure 7 (b) has high amplitude impulses and also its magnitude lies in the range of +35 to -30 mV which is much higher in comparison to amplitude of the signal for the defect free bearing. This indicates presence of defect on the defect in the bearing. Further for the defect identification Empirical Mode Decomposition technique is applied. Raw signal of the non-defective bearing is shown in below figure.



(a)



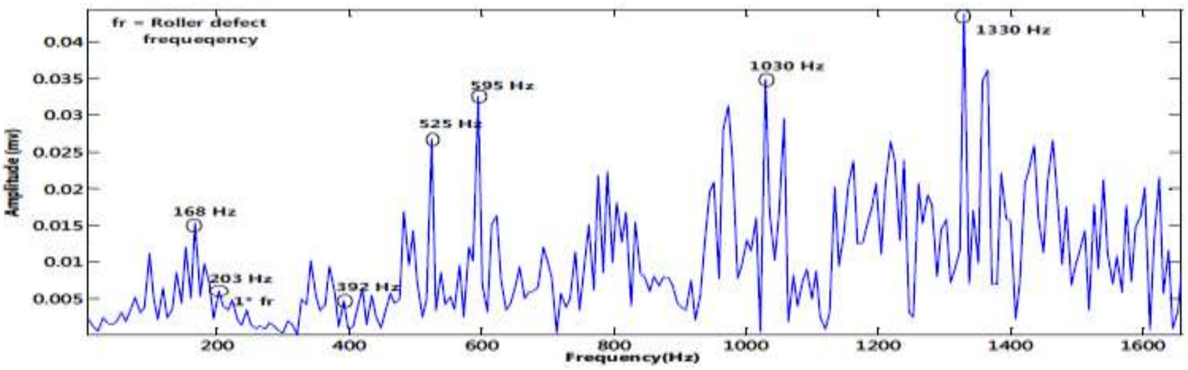
(b)

Figure 8. Raw signals of the non-defective bearing (Figure (a)) and bearing with single roller groove defect (Figure (b))

FFT of the defective signal (shown in figure 7 (b)) is obtained and the corresponding plot is shown in Figure 8. In this plot we didn't see any peak at the defect frequency. In Figure 8 the roller defect frequency (200.2 Hz) is hardly visible and most likely to be missed out in presence of more noise. Further, the peaks at BCF and its harmonics are so small that looking for a trend of amplitude is quite difficult. Thus it is evident that simple FFT analysis is not a suitable technique for bearing faults analysis.

Empirical mode decomposition (EMD) of the raw signal is carried out and the corresponding IMFs (1-4) are shown in Figure 9. Only first four IMFs are shown because defect frequency lie in the higher IMFs. As lower IMFs contain lower frequency component so lower IMFs are neglected. IMF selection in the present work is carried out according to the maximum kurtosis

Figure 9: FFT of the roller single groove defect obtained from the raw signal



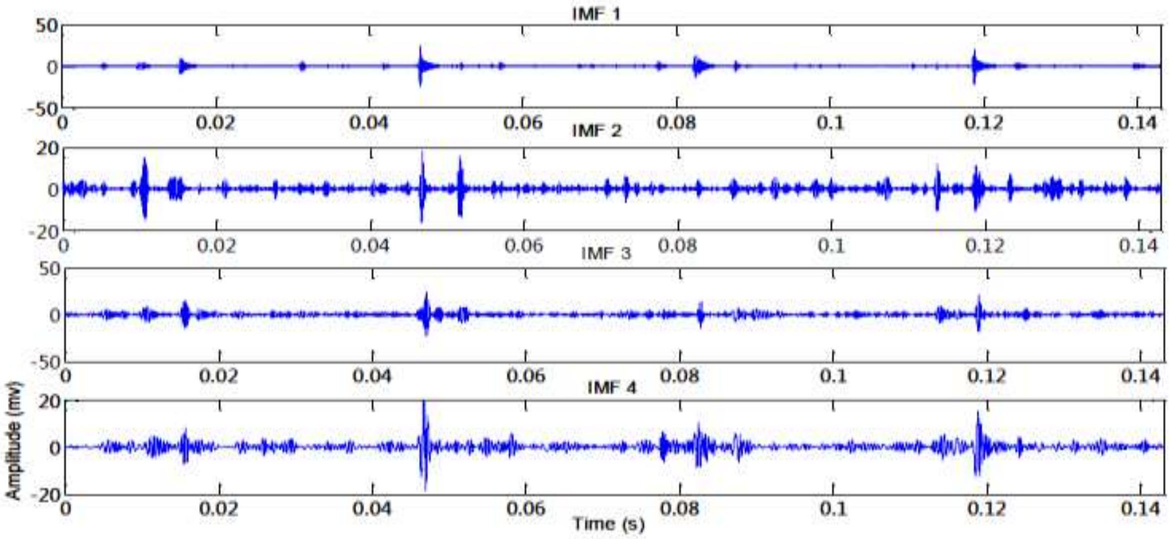


Figure 10. Time waveform of the first 4 IMFs for single roller groove defect

Table 3. Kurtosis of the first 4 IMFs for defect on the rollers

IMF	IMF1	IMF2	IMF3	IMF4
Kurtosis for single roller groove defect (at 0º)	62.934	20.341	16.518	20.998

Enveloping of the IMF is carried out and the corresponding Envelope spectrum and Envelope signal of the selected IMF is shown in Figure 10 and Figure 11 respectively.

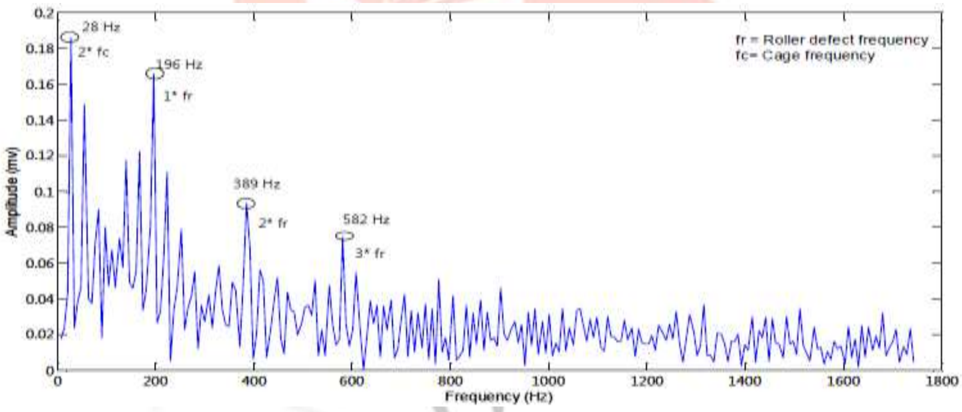


Figure 11. Envelope spectrum (FFT) of IMF1 for single roller groove defect

In the envelope spectrum (shown in figure 10) we observe a highest peak at 28 Hz. Which is second harmonics of cage frequency (14.2 Hz) and another high peak at 196 Hz, which is close to theoretical defect frequency of 200.2 Hz. Thus peak at 196 Hz in this plot indicate roller defect frequency. In this plot we observe roller defect frequency

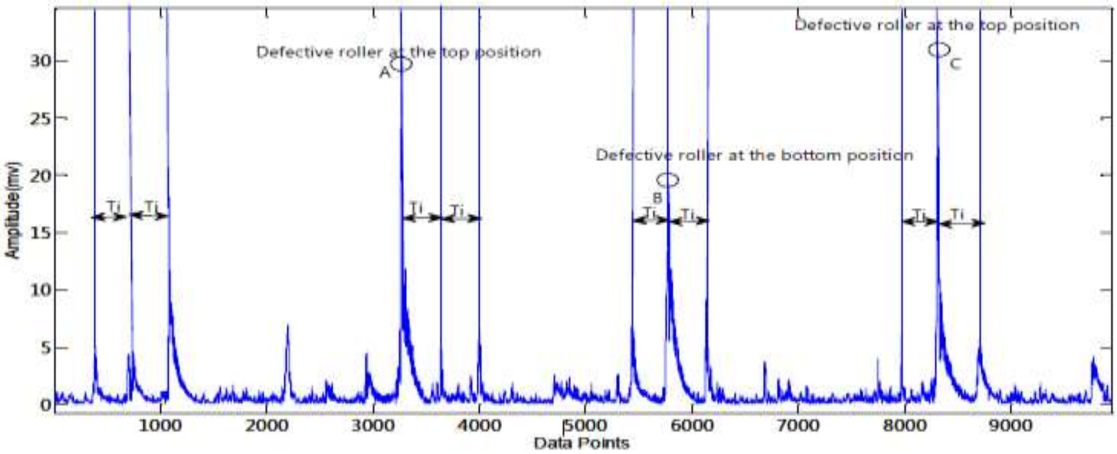


Figure 12. Envelope signal of the IMF1 for single roller groove defect

Envelope signal of the selected IMF of 0.1428 seconds duration is shown in Figure 11. Here highest peak is observed at A, which is due to defective roller impact at the outer race at top position in front of accelerometer. Roller after completing one complete cage rotation (5043 data points) reach again at the top in front of accelerometer, the same criteria can be observed by high magnitude peak at C. In between these peaks we see another high peak at B whose magnitude is less than peak at A and C, which indicate defective roller is at bottom position. Magnitude of the peak at B is less than peak at A and C, this because accelerometer is uni-axial and it can capture only vertical acceleration. Vertical acceleration is maximum at top and bottom vertical position, since accelerometer in mounted on the top of the bearing casing so vibration produced at the bottom position get damped while reaching the accelerometer due to damping effect of bearing structure. So peak at B is due to defective roller at the bottom position. Roller impact interval (Ti) (Impact interval is the time interval between the two impacts) of 358 data points (0.00511 seconds) is calculated by taking average from 12 bursts when defective roller strikes at the top and bottom position on the bearing, which also indicates defective frequency of 195.7Hz (approximately 196 Hz).

5. 2 Results: From the above discussion it is concluded that, when the FFT is directly applied to the raw signal, it is not able to identify the defects in the bearings. But using empirical mode decomposition (EMD) technique the defects in the rollers at different positions can be identified. So it appears that EMD is very powerful signal processing technique in the fault diagnosis of the rolling elements of bearings. In the present work we have used EMD along with envelope analysis to detect the faults of the roller bearings. The experimental result shows that the proposed method can effectively diagnose the faults on the rolling element bearing. Experiments in this study have verified that the proposed procedure of using the suitable IMF is a superior approach for the identification of defects in the bearings. As far the accuracy of the proposed method is concerned, there is inappreciable deviation in the results from the theoretical values as shown in the table 4.

Table 4. Compression of theoretical and experimental defect frequency

Fault type	Theoretical value of defect frequency	Experimental value of defect frequency	Percentage (%) deviation
Single roller groove defect (0^0)	200.2	196	2.1

6 CONCLUSIONS: Overall conclusions of the conducted work are as follows:

- Empirical Mode Decomposition (EMD) is a self-adaptive signal processing method that can be applied to non-linear and non-stationary processes effectively. It improves traditional FFT method in applying harmonic functions to show all kinds of faulty signals into a sequence of amplitude modulation/frequency modulation.
- Frequency band range in each IMF ranges from high to low frequency in the signal. EMD can be combined with the envelope analysis as a detecting tool for the bearing fault analysis.
- Maximum kurtosis criteria for the selection of IMF give batter result. Higher value of kurtosis reveals the presence of defects in the bearings. The IMF with maximum kurtosis is used for the analysis of defect. For single roller groove defect IMF1 has the maximum kurtosis value of 62.934.
- Comparison between the traditional FFT and proposed work shows that, if the FFT is directly applied to the raw signal of the defective bearings then defects in the rollers are difficult to identify, whereas, the EMD easily detect the presence of defects in the rollers.

- The results obtained by the proposed method are very close to the theoretical values of the defects. The roller defect frequency, for single roller groove deviate 2.1 % from the theoretical value of the defect frequency.

REFERENCES

[1] Hale, V. and Mathew, J. 1995. High and low speed bearings, in Condition Monitoring Frontiers, the second Forum. Melbourne, Australia pp. 21-30.

[2] Chen, C. and Mo. 2004. A method for intelligent fault diagnosis of rotating machinery. *Digital Signal Processing*. 14(3): 203–210

[3] Friswell, M. I., Litak, G. and Sawicki, J. T. 2010. Crack identification in rotating machines with active bearings. Proceeding ISMA, Leuven (Belgium). pp. 2843-2856

[4] Alfredson, R. J. and Mathew, J. 1985. Time domain methods for monitoring the condition of rolling element bearings. *Mechanical Engineering Transactions Institution of Engineers, Australia.* ME 10 (2): 102-107.

[5] Tandon, N. and Choudhury, A. 1999. A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings. *Tribology International*. 32 (8): 469-480

[6] Igarashi, T. and Hamada, H. 1982. Studies on the vibration and sound of defective rolling bearings. (First report: vibration of ball bearings with one defect) Bull. *JSME*. 25(204): 994-1001.

[7] Brown, D. N. 1989. Envelope analysis detects bearing faults before major damage occurs. *Pulp & Paper*. 63: 113- 117.

[8] Taylor, J. I. 1980. Identification of the bearing defects by spectral analysis. *ASME Journal of Mechanical Design.* 102: 199-203.

[9] McFadden, P. D., and Smith, J. D. 1984. Vibration monitoring of rolling element bearings by the high frequency resonance techniques-a review. *Tribology International.* 17: 3-10.

[10] Osugawu, C., and Thomas, D. 1982. Effect of inter-modulation and quasi-periodic instability in the diagnosis of the rolling element incipient defect. *Trans ASME, Journal of Mechanical Design.* 104 (2): 296-302.

[11] Miyachi, T. and Seki, K. 1986. An investigation of the early detection of defects in ball bearings using vibration monitoring - practical limit of detectability and growth speed of defects. Proceedings of the International Conference on Rotor dynamics, JSMEIFToMM Tokyo. pp. 403-408.

[12] Mathew, J., and Alfredson, R. J. 1984. The condition monitoring of rolling element bearings using vibration analysis. *ASME, Journal of Vibration an Acoustics.* 106: 447-453.

[13] Heng, R. B. W. and Nor, M. J .M. 1998. Statistical analysis of sound and vibration signals for monitoring rolling element bearing condition. *Applied Acoustics*. 53: 211-226.

[14] Williams, T., Ribadeneira, X., Billington, S., and Kurfess, T. 2001. Rolling element bearing diagnostics is run-to-failure lifetime testing. *Mechanical System and Signal Processing.* 15(5): 979-993.

[15] Kankar, P.K., Sharma, S. C., Harsha, S.P. 2011. Rolling element bearing fault diagnosis using wavelet transform. *Neurocomputing.* 74: 1638–1645.

[16] McFadden, P. D., and Smith, J. D. 1984. Vibration monitoring of rolling element bearings by the high frequency resonance techniques-a review. *Tribology International.* 17: 3-10

[17] Mcfadden, P. D., and Toozhy, M. M. 2000. Application of synchronous averaging to vibration monitoring of rolling element bearings. *Mechanical Systems and Signal Processing.* 14(6): 891–906.

[18] Huang, N. E., Shen, Z., Long, S. R. 1998. The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. Proceeding of the Royal Society London. (454) pp. 903–95

[19] Huang, N.E., Samuel, S. P. S. 2005. Hilbert-Huang transform and its applications. Singapore: World Scientific.

[20] Geramitchioski, T. and Trajcevski, L. 2011. Prediction of rolling bearings defect in motor-fan using vibration signal analysis. *Machine Design.* 3(3): 211-216.

[21] Wang, D., Miao, Q., Fan, X. and Huang, H. Z. 2009. Rolling element bearing fault detection using an improved combination of Hilbert and Wavelet transforms. *Journal of Mechanical Science and Technology.* 23: 3292-3301.

[22] Mobely, R. K. 2001. Plant Engineers Hand Book. Butterworth-Heinemann.

[23] Cochran, W. T., Colley J. W. and Favin D. L. 1967. What is the Fast Fourier Transform? *IEEE Transactions on Audio and Electro Autistic.* AU-15, NO. 2.

[24] Proakis, J. G. and Salehi, M. 2000. Contemporary Communication Systems.Book Ware Companion Series.

[25] Kerschen, G., Vakakis, A. F., Lee, Y. S., McFarland, D.M. and Bergman, L.A. 2009. Toward a Fundamental Understanding of the Hilbert-Huang Transform in Nonlinear Structural Dynamics. *Journal of Vibration and Control.* 15: 1563-1579.

[26] Heng, R. B. W. and Nor, M. J .M. 1998. Statistical analysis of sound and vibration signals for monitoring rolling element bearing condition. *Applied Acoustics*. 53: 211-226.