Conditioning Monitoring of Ball Bearing Using Vibrational Analysis

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Abstract - *An overview of the research on vibration analysis-based ball-bearing condition monitoring is provided in this abstract. The study is concerned with the fundamental ideas, approaches, and advantages of using vibration analysis as a diagnostic tool to evaluate the condition of ball bearings.*

Beginning with a discussion of ball-bearing operation principles, the study stresses the significance of dependable and effective bearing performance. Then, it examines typical failure modes. The common failure modes of ball bearings are then discussed, including flaws like fatigue, misalignment, lubrication problems, and high loading.

The abstract then explores the theory of vibration analysis and how it might be used to identify bearing defects. To pinpoint the distinctive frequencies connected to particular defect kinds, vibration signatures recorded from sensors put on the machinery are analyzed. To extract useful information from the vibration signals, signal processing techniques including Fourier analysis, envelope analysis, and time-frequency analysis are used.

The abstract also emphasizes the advantages of using vibration analysis to check ball-bearing quality. Continuous vibration pattern monitoring makes it feasible to identify bearing defects early, enabling prompt maintenance actions. This proactive technique not only stops unanticipated failures and output losses but also increases the bearing's lifespan and lowers maintenance expenses.

Key Words: **Condition monitoring, fault diagnosis, BPFO, BPFI, BSF, FTF**

1. INTRODUCTION

The project is to verify bearing faults is one of the most challenging tasks for bearing condition monitoring. Bearing is frequently used in household and industrial machines. The primary purpose of a bearing is to prevent direct contact between two parts when they are in relative motion. Even a minor failure in this section negatively affects the overall functioning of the machine. As a result, the industry faces financial losses and this loss potentially results in the failures. Bearing failure is mainly due to the following reasons: improper manufacturing, improper design, improper lubrication, overloading or mounting, and misalignment of bearing races. For the proper functioning of the machines, it is, therefore, necessary to diagnose the fault. However, the effectiveness of this technology depends on its proper implementation. Therefore, even a small defect in the rolling element bearing has to be admitted and rectified as soon as possible. The main defects are localized and distributed defects. The localized defect occurs due to pitting, cracks, and tears due to fatigue and wear. The distributed defect includes surface roughness, waviness, and misalignment races. The principal causes of these defects can result in wear or manufacturing error. Different techniques are employed to detect a failure in the bearing. While time-domain approaches can point to a bearing failure, they cannot pinpoint its exact location. The position of a bearing defect can be located using frequency domain techniques.

1.1 Problem Definition

In our project, we are mainly focusing on the Faults diagnosis of rolling element bearings. Therefore, we are mainly considering the following mentioned points:

i.When a bearing falls short of its predicted lifespan or projected performance standards, it is said to have failed. In all applications, they may nevertheless break abruptly or prematurely despite meticulous planning and routine maintenance.

ii. Less than 30% of the bearing ever meet their determined fatigue limit and 'wear out' in their applications. If the bearing malfunctions and fails, it is best to identify the cause of the problem.

iii. It is necessary to identify the condition of the bearing in assembly.

1.2 Objective

The core objective of this project is to diagnose the faults of the rolling element ball bearing using FFT. The main focus of the project is to take readings using FFT and categories defects based on components of bearing. Which are the inner race, outer race, cage, and ball of the bearing.

To complete the project, the following objectives are considered:

- Testing and optimizing the system to ensure maximum energy efficiency and output.
- To engrave defects on bearing using wire EDM.
- To Find theoretical and experimental results.

- To verify theoretical and experimental results of vibrations.

2. Rolling Element Ball Bearing

A rolling element ball bearing is a type of bearing that has steel balls or rollers sandwiched between the inner and outer raceways. These "roll" along the raceways like balls or rollers, reducing friction and allowing the bearing to rotate smoothly.

Automotive, industrial machinery, appliances, and other industries employ rolling-element ball bearings extensively. They provide several benefits, including reduced friction, a large capacity for carrying loads, durability, and the potential to function at high speeds. Even load distribution by the balls or rollers reduces wear and increases bearing longevity.

Deep groove ball bearings, angular contact ball bearings, thrust ball bearings, and self-aligning ball bearings are some of the several kinds of rolling element ball bearings. Each type is made to meet a certain load and speed requirement.

The best performance and lifetime of rolling element ball bearings depend on routine maintenance and lubrication. Their effective performance is further aided by proper installation, alignment, and contamination protection. [2].

2.1 Components and Description

Ball bearings consist of components that work together to enable smooth rotation and reduce friction. The main components of ball bearings include:

i. Outer Race - The outermost part of the bearing is often referred to as the outer ring. It supports the other bearing parts and houses them. As the outside raceway for the balls, the outer ring normally has a smooth, cylindrical, or spherical surface.

ii. Inner Race - The spinning shaft is fitted with the inner ring, also known as the inner ring. It supports the shaft and secures it inside the bearing assembly. The inner ring functions as the inner raceway for the balls and, like the outer ring, has a smooth, cylindrical, or spherical surface.

iii. Balls The rolling components of the bearing are the balls, which are situated in between the inner and outer rings. Although ceramic balls are occasionally used, they are primarily constructed of steel. Depending on the bearing's size and design, different numbers of balls may be used. As the balls move along the raceways, the load is distributed and friction is reduced.

iv. Cage or retainer - The cage or retainer is a part that secures the balls and preserves the ideal distance between them. By preventing the balls from making contact with one another, it ensures friction-free operation. Metal or synthetic polymers are just a couple of the materials that can be used to create the cage.

v. Seals - Seals are parts that keep the bearing lubricated and shield it from outside elements. seals are typically metal plates that cover the bearing's sides and act as a physical barrier against debris like dirt and dust. Instead, seals offer a more reliable seal against impurities and moisture and are typically composed of rubber or plastic. Depending on the desired amount of protection, shields, and seals may be installed on either one or both sides of the bearing.

2.2 Defects

Bearings can experience various defects that can impact their performance and longevity. Some common defects include:

1. Wear: The raceways, balls, and rollers in bearings can become worn out over time through friction and constant use. Increased friction, a decrease in load-carrying capacity, and eventually a failure of the bearing can all be effects of wear.

2. The bearing material may become fatigued as a result of repeated stress cycles, which can lead to cracks, spalling, or pitting on the raceways or rolling elements. The bearing may become less durable due to wear and eventually fail.

3. Issues with lubrication: Poor or insufficient lubrication can result in issues like insufficient film thickness, higher friction, and accelerated wear. Dry running can result from insufficient lubrication, while over-lubrication can contribute to overheating and excessive drag.

4. Contamination: The presence of impurities, such as dust, moisture, or dirt, can cause the bearing surfaces to wear down more quickly. Contaminants can cause corrosion, abrasive wear, or the buildup of debris, which can impair efficient performance.

5. Misalignment: The bearing's incorrect alignment can lead to uneven loads, more friction, and early wear. Installation mistakes or outside factors acting on the bearing assembly might cause misalignment.

6. Overloading: Loads that are too great for the bearing to handle can lead to excessive stress, distortion, and failure. Improper application design or running circumstances may lead to overloading.

7. Improper handling or installation: Damage, brinelling (indentation), or misalignment of the bearing components can result from improper handling or poor installation methods, which can reduce the performance and longevity of the bearings.

3. Methodology and Components

3.1 Fast Fourier Transform

The "Fast Fourier Transform" (FFT) is a critical measurement method in the area of measuring audio and acoustics. In the process, it dissects a signal into its spectral components and provides frequency information about the signal. For quality assurance, defect investigation, and machine or system state monitoring, FFTs are employed. We must first translate vibrational motion into electric form to analyze vibration in signal form. Machine vibration is the only source of physical motion at the microscopic level. These vibrations are invisible to the naked eye. We use a variety of sensors, including proximity sensors, seismic sensors, accelerometers, and more, to analyze these micro-vibrations. To measure the vibration that is produced, we are utilizing an accelerometer in this experiment. Electrical signals produced by an accelerometer are subsequently transmitted to a data collector or analyzer, which then evaluates the data and provides FFT graphs and other parameters. We have data in the frequency domain to use an FFT analyzer to find any machine faults, but accelerometer data is in the time domain. As a result, we must translate the data from the time domain into the frequency domain. This task is performed using the Fast Fourier Transformation (FFT) approach.[6]

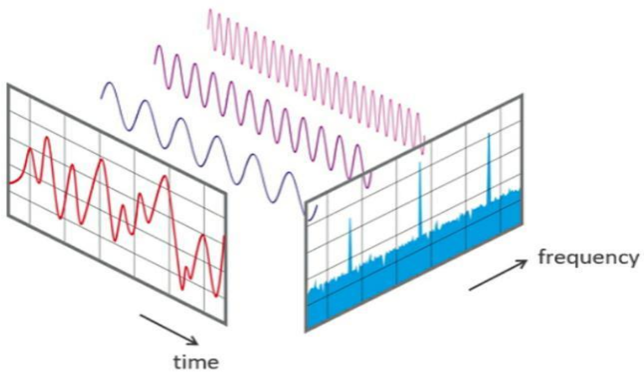


Fig -1: View of signal in time and frequency domain

3.2 Analyzer System:

Signal analysis was done with the CEMB N600. An FFT analyzer with two channels is used. to read the rpm/Hz reading, it has a photocell. Seismic sensors are connected and being used by this machine. Sensors are selected such that allow it to measure displacement, velocity, and acceleration.

Fig -2: CEMB N600 FFT

3.3 Accelerometer

An accelerometer is a sensor device used to detect acceleration, which is the rate at which velocity changes with time. It is a vector with a direction and a magnitude. A “g” is the acceleration measurement for gravity, which is equal to 9.81 m/s, and is the unit of measurement used by accelerometers. From a basic water tube with an air bubble indicating the direction of the acceleration to an integrated Circuit that can be mounted on a circuit board, and accelerometers have evolved. An accelerometer can gauge an object's motion, vibrations, shocks, tilt, and collisions.

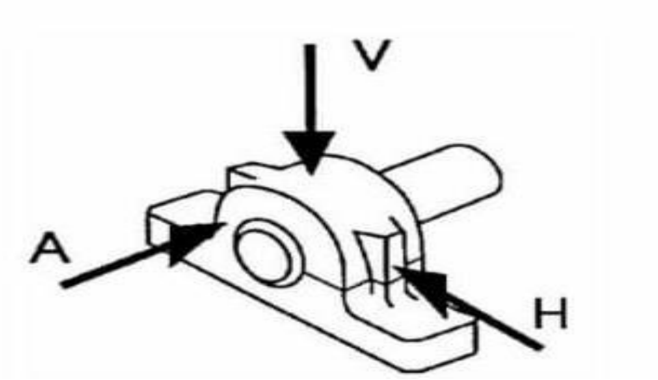


Fig -3: Accelerometer Position

3.4 Data Acquisition System

A data acquisition system (DAS) is the process of storing signals that measure a physical thing and converting it into a digital form that can be stored on the computer. A hardware and software combination is referred to as a data acquisition system. It gauges or regulates the physical traits found in the real world. Sensors, actuators, DAQ hardware, signal conditioning hardware, and a computer with DAQ software make up a complete data acquisition system. Crucial parts make up data acquisition systems. These are listed below:

Signal Conditioning: The main purpose of signal conditioning is to condition signals so that they can be converted into digital signals to the Analog Digital subsystem and can be stored and analyzed. Signal conditioning includes range matching, amplification, filtering, converting, and isolation. It includes other processes which can make the data suitable after Conditioning.

Analog to Digital Converter: Output of the most physical phenomenon after the signal condition is in analog form. It is converted to digital forms by an Analog Digital converter system. DEWE 43 V consists of both signal conditioning and an A/D converter.

Specification of DEWE. 43 V

No of channels – 8

Inputs – Voltage

Power supply - 9-36 V DC

IP rating - IP50

Sensor supply - +5V+12V

Sampling Rate - Simultaneous 200 kS/sec

ADC type - 24-bit sigma-delta with an anti-aliasing filter

Input type - Differential

In condition monitoring, data recorders are required to preserve and analyze data collected by transducers. Multichannel digital data recorders with modular units for analog data acquisition from a variety of transducers such as accelerometers, thermocouples, strain gauges, optical encoders, and voltage probes are available. Digital data can be easily shared and moved between computers using USB devices and the Internet. Simple math operations and even FFT can be performed on the data and presented on the screen because it is recorded in digital format.

Fig -4: USB Data acquisition system

3.5 Bearing Specifications:

Fig -5: Bearings-: 1207 EKTN9

- Outer race diameter- 72mm
- Inner race diameter- 35mm
- Thickness-17 mm
- Ball diameter- 9 mm
- Pitch diameter-51
- No. of balls- 30
- Bore type Tapered- 1:12
- Material, bearing- Bearing steel

This bearing is used for BPFO & BPFI

Fig -6: Bearings-: NSK 1207 K

- Outer race diameter- 72 mm
- Inner race diameter- 35 mm
- Thickness-17 mm
- Ball diameter- 8 mm

- Pitch diameter-51
- No. of balls- 32
- Bore type Tapered- 1:12
- Material, bearing- Bearing steel

This bearing is used for BSF & FTF

3.6 Experimental Bearing Test Rig

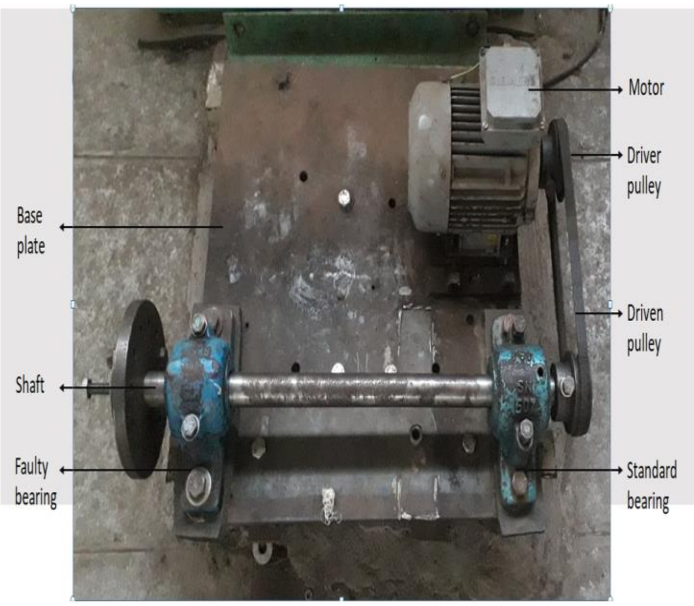


Fig -7: Test Rig Setup

Fig -6: Setup with DAS connection

4. Defects on the Bearing

As per the convenience of defect creation, we have chosen two different bearings with different manufacturers but in the end, this selection of both bearings never deviates from our objectives of the project.

Fig -7: Outer race defect

Fig -8: Inner race defect

Fig -9: Ball defect

Fig -8: Cage defect

5. Calculation

5.1 Theoretical formulae for bearing failure frequency

As a result of using the bearing at excessive speeds and incorrect loading conditions, rolling bearing faults may manifest themselves prematurely. As an alternative, they might simply be created as a by-product of the bearing's natural wear process. Historically, regardless of wear, machines with rolling element bearings would have their bearings replaced regularly as part of the routine maintenance cycle. This would be done to prevent a bearing failure in the future, which would force an unfavorable machine stoppage. However, a developing tendency is to continuously check on the status of rolling element bearings so that bearing wear can be discovered early and the engineer can make sure the bearing is replaced. conveniently before the bearing fully fails. The raceway, the rolling elements, or the cage may develop defects in the bearing; subsequent vibrations are forced as a result of an impact between the defect and other bearing components, and the frequency of the resulting vibrations is largely dependent on the frequency of impacting. The following formulas can be used to determine these frequencies, which are also known as characteristic frequencies.

Outer race frequency (BPFO) = $n/2\ N/60[\,1 - d\,/D \cos\alpha]$

Inner race frequency (BPFI) = $n/2\ N/60[\,1 + d\,/D \cos\alpha]$

Rolling element frequency (BPF) = $n/2(N/60)\ [(1\text{-}d^2/D^2)\ \text{Cos}^2\ \alpha]$

Fundamental trained frequency (FTF) = $N/120\ [1 - d/D \cos\alpha]$

Where, N=Speed of Shaft in RPM

α =contact angle,

n=the number of rolling elements

d=mean diameter of rolling element

D=pitch diameter

The characteristic frequencies are easy to compute, however, defect detection might be difficult due to many factors. As bearing wear progresses, the frequency spectrum moves even more, with some of the characteristic frequencies being quite close to rotational speed harmonics. Sometimes the defective frequency's higher-order harmonics can be detected, possibly with their sidebands, and they can dominate the spectrum.

5.2 Results using 1000 RPM:

Table -1: 1000 RPM Calculations

1207 EKTN9 **Ball pass frequency of the outer race (BPFO)* *BPFO= $n/2\ N/60[\,1 - d/D \cos\alpha]$* ***BPFO= 112.38 Hz***
1207 EKTN9

Ball pass frequency of the inner race (BPFI)* *BPFI= n/2 N/60[1 + d/D cos α]* ***BPFI=154.17 Hz*
NSK 1207 K **Ball spin frequency (BSF)* BSF= n/2(N/60) [(1-d²/D²) Cos² α] ***BSF=121.38 Hz***
NSK 1207 K **Fundamental Train Frequency (FTF)* *FTF= N/120 [1 – d/D cos α]* ***FTF= 6.17 Hz***

The above table is theoretical calculation for all four bearing defects which we have considered in the scope of this project on 1000 RPM. The above results are calculated as per standard formulas defined for bearing defect frequencies.

5.3 Results using 2000 RPM

Table -2: 2000 RPM Calculations

1207 EKTN9 **Ball pass frequency of the outer race (BPFO)* *BPFO= n/2 N/60[1 - d/D cos α]* *BPFO= 224.83 Hz*
1207 EKTN9 **Ball pass frequency of the inner race (BPFI)* *BPFI= n/2 N/60[1 + d/D cos α]* *BPFI=308.44 Hz*
NSK 1207 K **Ball spin frequency (BSF)* BSF= n/2(N/60) [(1-d²/D²) Cos² α] *BSF= 242.19 Hz*
NSK 1207 K **Fundamental Train Frequency (FTF)* *FTF= N/120 [1 – d/D cos α]* *FTF= 6.17 Hz*

The above table is theoretical calculation for all four bearing defects which we have considered in the scope of this project on 2000 RPM.

6. Results & Discussion

For experimental reading, we used different instruments like FFT (Fast Fourier Transform), Accelerometer, Tachometer, Data Acquisition System (DEWE 43), VFD, and DeweSoft software. By varying the speed of the shaft (1000 and 2000 RPM) using VFD we store frequency results in DeweSoft Software for different defective bearings such as outer race, inner race, ball, and cage defect. For proper analysis and reading of gathered results we converted those results into MATLAB file format and using MATLAB signal processing program we generated frequency graphs of acceleration(g) vs frequency (Hz).

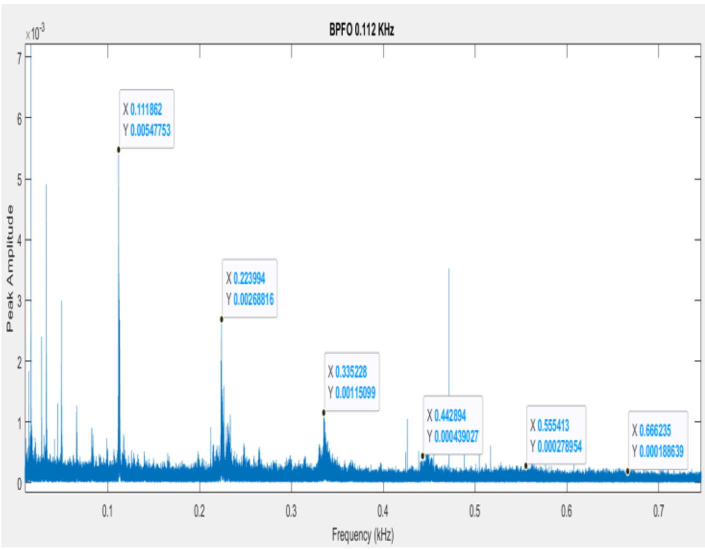
MATLAB code used for signal processing:

```
clc
close all
fs = 20000; % sampling frequency
figure(1)
plot(time,acc)
figure(2)
envspectrum(acc - mean(acc), fs)
```

The following are the generated graphs using MATLAB

6.1 At 1000 RPM

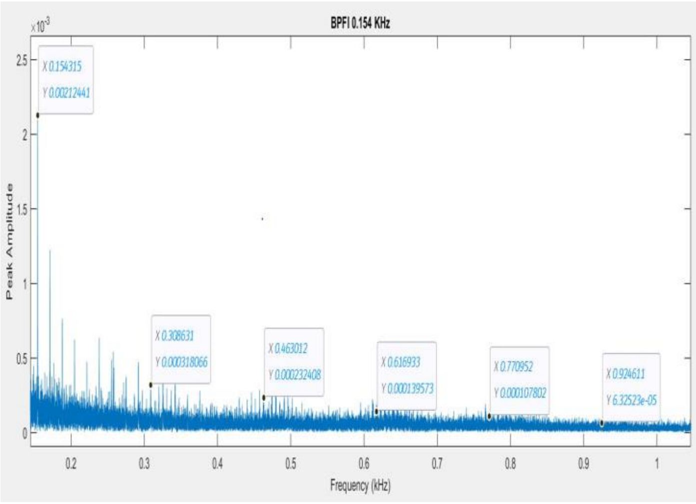
6.1.1 BPFO



Graph -1: BPFO at 1000 RPM

The above graph is the frequency spectrum of Ball pass frequency outer race at 1000 RPM where our theoretical result for this defect is 0.112 KHz and in the experiment we are getting a peak at 0.111 KHz with its corresponding decreasing harmonics at 0.223 KHz, 0.335 KHz, 0.442 KHz, 0.555 KHz hence we can conclude that this bearing is with defect at its outer race and both theoretical and experimental results are same.

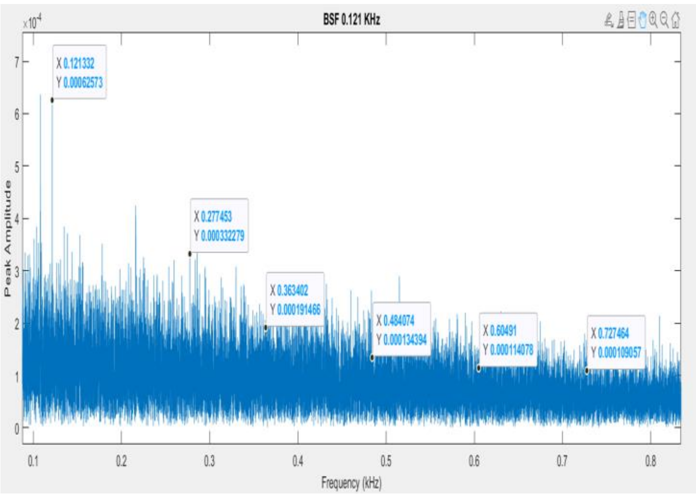
6.1.2 BPFI



Graph -2: BPFI at 1000 RPM

The above graph is the frequency spectrum of Ball pass frequency inner race at 1000 RPM where our theoretical result for this defect is 0.154 KHz and in the experiment, we are getting a peak at 0.154 KHz with its corresponding decreasing harmonics at 0.308 KHz, 0.463 KHz, 0.616 KHz, 0.770 KHz hence we can conclude that this bearing is with defect at its inner race and both theoretical and experimental results are same.

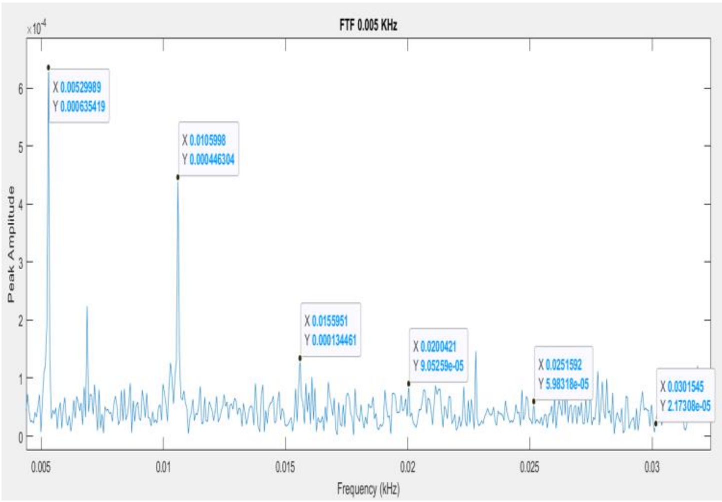
6.1.3 BSF



Graph -3: BSF at 1000 RPM

The above graph is the frequency spectrum of Ball spin frequency at 1000 RPM where our theoretical result for this defect is 0.121 KHz and in the experiment we are getting a peak at 0.121 KHz with its corresponding decreasing harmonics at 0.227 KHz, 0.363 KHz, 0.484 KHz, 0.604 KHz hence we can conclude that this bearing is with defect at its rolling element and both theoretical and experimental results are same.

6.1.4 FTF

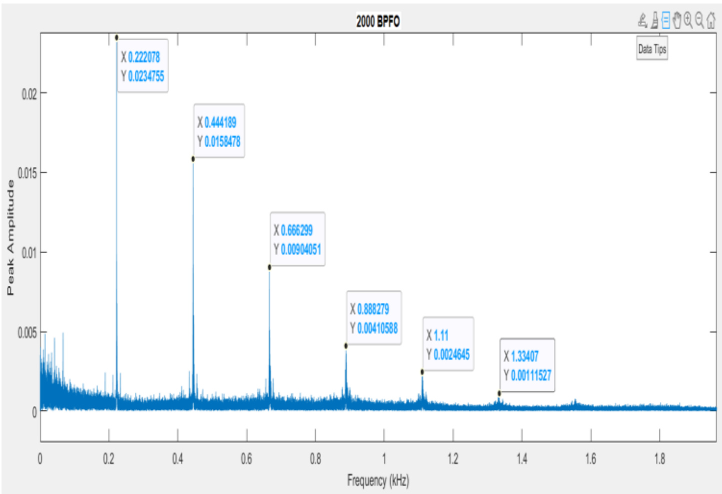


Graph -4: FTF at 1000 RPM

The above picture is the frequency spectrum of fundamental train frequency where our theoretical result for this defect based on geometry and speed is 0.006 KHz and in the experiment, we are getting a peak at 0.005 KHz with its corresponding decreasing harmonics at 0.010 KHz,0.015 KHz, 0.020 KHz, 0.025 KHz hence we can conclude that this bearing is with defect at its outer race and both theoretical and experimental results are same.

6.2 At 2000 RPM

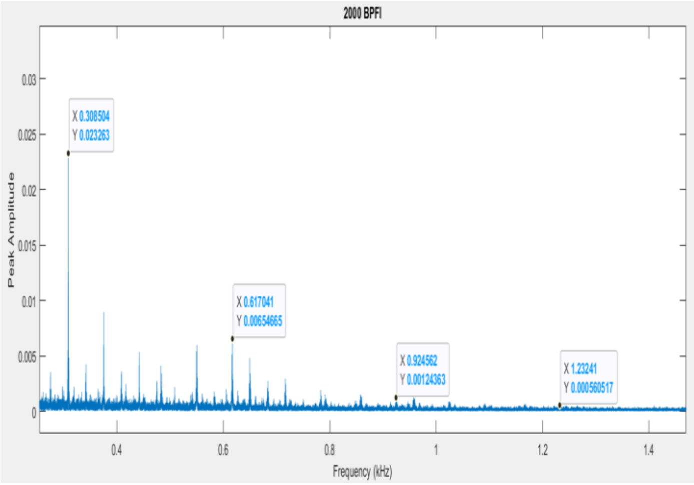
6.2.1 BPFO



Graph -5: BPFO at 2000 RPM

The above graph is the frequency spectrum of Ball pass frequency outer race at 2000 RPM where our theoretical result for this defect is 0.224 KHz and in the experiment we are getting a peak at 0.222 KHz with its corresponding decreasing harmonics at 0.444 KHz,0.666 KHz, 0.888 KHz, 1.11 KHz hence we can conclude that this bearing is with defect at its outer race and both theoretical and experimental results are same.

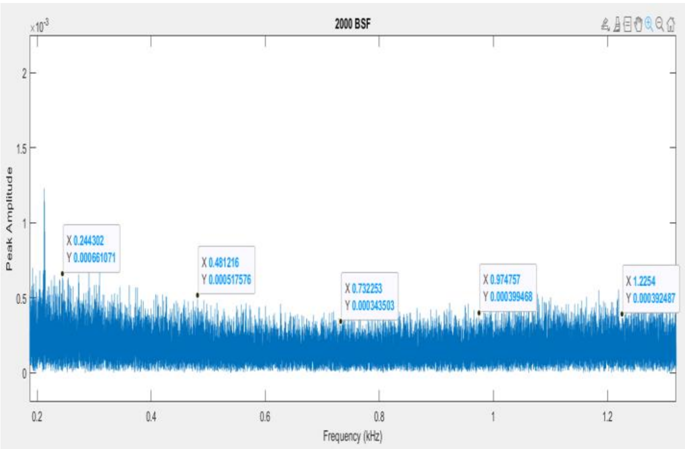
6.2.2 BPFI



Graph -6: BPFI at 2000 RPM

The above graph is the frequency spectrum of Ball pass frequency inner race at 2000 RPM where our theoretical result for this defect is 0.308 KHz and in the experiment, we are getting a peak at 0.308 KHz with its corresponding decreasing harmonics at 0.617 KHz, 0.924 KHz, 1.232 KHz hence we can conclude that this bearing is with defect at its inner race and both theoretical and experimental results are same.

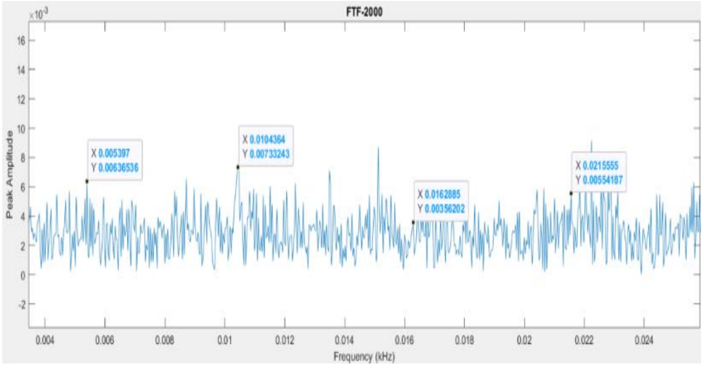
6.2.3 BSF



Graph -7: BPFO at 2000 RPM

The above graph is the frequency spectrum of Ball spin frequency at 2000 RPM where our theoretical result for this defect is 0.244 KHz and in the experiment we are getting a peak at 0.244 KHz with its corresponding decreasing harmonics at 0.481 KHz, 0.732 KHz, 0.974 KHz, 1.225 KHz hence we can conclude that this bearing is with defect at its rolling element and both theoretical and experimental results are same.

6.2.4 FTF



Graph -8: FTF at 2000 RPM

The above graph is the frequency spectrum of fundamental train frequency at 2000 RPM where our theoretical result for this defect is 0.006 KHz and in the experiment we are getting a peak at 0.005 KHz with its corresponding decreasing harmonics at 0.010 KHz, 0.016 KHz, we can conclude that this bearing is with defect at its rolling element and both theoretical and experimental results are same.

7. CONCLUSIONS

From the data gathered through experimental results, we can interpret the following conclusions:

Vibration analysis in enveloping spectrum or frequency vs acceleration is easy to measure and widely used in various frequency-measuring domains. While examining experimental results it also observed that frequency vs acceleration data is easy to read and understand.

The frequency generated by using theoretical or we can say standard formulae of BPFO, BPFI, BSF, FTF, and the frequency generated from the experiment is the same.

As one of the objectives of the project, we verified both theoretical and experimental results of bearing failure and condition monitoring so that next time only by measuring frequency in the frequency domain and having knowledge of bearing characteristics we can monitor the condition of the bearing.

8. Future Scope

Diagnostics of components such as rotating shafts, bearings, gears, and pumps are all included in the large field of vibration monitoring and fault finding in rotating machinery. The various fault types that are seen in these parts and the methodologies for diagnosing them include vibration analysis and model-based techniques.

●Fuzzy logic or Machine learning makes it possible to directly find out bearing defect frequency using bearing dimensions.

●Also programming is possible to predict the type of defect bearing having based on measured frequency data.

●Run time automatic and remote bearing frequency monitoring is possible.

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