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Vibration Monitoring For Rolling Element Bearing Using Fast Fourier Transform

H.H.Goh, C.M.Soo, B.C.Kok, and K.C.Goh

***Abstract*— Many types of equipment today are required in service well for 24 hours a day and beyond their intended lifetimes. Then, to dismantle them for inspection from time to time is very expensive while the owners need to consider all the faults before making the decision. Therefore, vibration signature is introduced to help the owners to decide based on all the relevant information taken. Vibration signature is an essential tool to detect motor problems, which can identify the specific faults like bearing or gears, or rotor imbalances without interrupting the operation of the motor. The techniques used in the vibration signature are field measurement with portable instruments, field recording followed by detailed analysis and permanent online monitoring. Each vibration shows the different characteristic that determined by the running speed, the number of poles on the rotor, the numbers of slot in the rotor or stator, and other variables. The objective of this project is to identify most of the bearing defects during the operation and provide valuable information to develop a maintenance schedule before the motor breaks down. All in all, from all the information, the owner can reduce the amount of unscheduled downtime while extend the running time of the motor and also decrease the energy costs.**

***Keywords*: Vibration analysis, Fast Fourier Transform**

I. Introduction

THE concept of vibration signature analysis is also called predictive maintenance. Vibration signature helps to determine if the motors are operating efficiently, and if problems can be expected in the future. It also tells us when to expect a downtime without disrupting the operation of the motor or altering it in anyway. Throughout this year, the economic developments and technological advances are leading the company to take on vibration analysis to prevent unpredicted downtime strive. Vibration analysis is very important to prevent the breakdown of motor. Monitoring the vibration signature produce by the motor bearing, shafts, misalignment, and also the electrical components does it. Vibration analysis will perform either online monitoring, recording or field measurement with portable instruments. The first thing to start the vibration analysis is to gather a complete data for the motor that means a full-spectrum vibration signature by mounting the sensor inside the motor. Hence, the data based on FFT are gathered. Then the data is compared to the healthy motor data, and is analyzed accordingly to defects by considering the frequencies at different points. Different frequency will lead to different defects such as unbalance, misalignment, mechanical looseness, bent shaft and sleeve bearings.

In this research, only two types of bearing will put into considerations, which are single row angular contact ball bearing and self-aligning ball bearing [1-3].

Figure 1. Single Row Angular Contact Ball Bearing (left) and Self Aligning Ball Bearing (right)

In this paper, a more detailed approach will be introduced, taking also into account types of bearing and types of bearing faults. First, a short overview of types of bearing in section II while in section III gives a brief understanding about the project methodology and section IV explains the experiment procedure. Section V is the case study for single row angular contact ball bearing. Then followed up by section VI, which are the analysis and discussion and section VII is for conclusion and recommendation.

Previous research papers related to this study regarding different methods used for vibration monitoring such as the stator current monitoring, neural network and vibration analysis using LABVIEW [6-12].

II. Bearing Faults

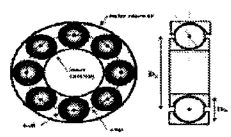

Figure 2. Geometry of a Rolling Element Bearing

Bearing faults are the most frequent faults in electric motors that are 41% according to an IEEE motor reliability study for large motors above 200hp [4].

In bearing faults, it is categorized into distributed and localized defects. Distributed defects affect a whole region and are difficult to characterize by distinct frequencies. Therefore, single point defects are localized and can be classified to four-affected element such as outer raceway defect, inner raceway defect, ball defect and cage defect. The defects frequency can be categorized as follow [1, 3]:

- Fundamental Train Frequency (FTF)

$$FTF = \frac{1}{2}(1 - \left(\frac{B}{P} x\ cos\theta\right) xf \text{ ----------------------(1)}$$

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- Ball Pass Inner Raceway Frequency (BPFI)

$$BPFI = \frac{N}{2}(1 + \left(\frac{B}{P}x\ cos\theta\right) xf \text{--------------------(2)}$$

- Ball Pass Outer Raceway Frequency (BPFO)

$$BPFO = \frac{N}{2}(1 - \left(\frac{B}{P}x\ cos\theta\right) xf \text{--------------------(3)}$$

- Ball Spin Frequency (BSF)

$$BSF = \frac{P}{2B}(1 - \left((\frac{B}{P})^2 x\ cos\theta^2\right) xf \text{-----------------(4)}$$

Where N = Number of ball
B = Ball Diameter
P = Pitch Diameter
F = Rotational Frequency
θ = Contact Angle

III. METHODOLOGY

A. Project Methodology

The method used to conduct this project is *vibration analysis* [14]. Vibration analysis is a method that measured at the external surfaces of a machine which contain a great deal of information as to the internal processes and a number of monitoring and analysis techniques can be applied to extract information from these signals[15, 17].

Portable instruments field measuring is a simplify operation where it can be carried out by people with the minimum training. Figure 3 shows the components used for the portable instrument. First, the accelerometer will mount on the motor. It will then pass by a data acquisition card. Lastly from the data acquisition card, the data will be stored inside the computer [16, 17]. One of the portable instruments used is accelerometer. An accelerometer is an electromechanical device that measures acceleration forces caused by moving or vibration objects whereas a data acquisition card is a card that collects the data sensed by accelerometer and converts this analog signal into a digital signal that can be read by the computer using CMS software.

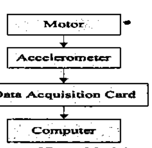

Figure 3. The Components of Portable Measurement Instruments

B. Flowchart

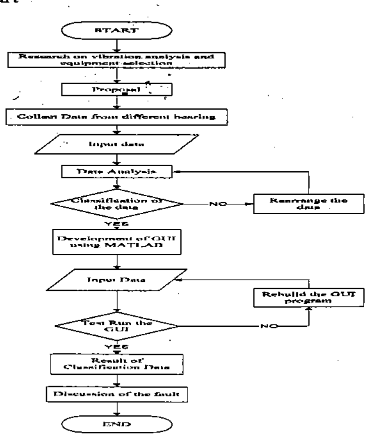

Figure 4. Flowchart for Vibration Analysis and GUI process

Figure 4 shows the flowchart for the project. The flow chart is divided into three phase. The first phase is where the research on vibration analysis and equipment is done. This will then follow up with the proposal and also bearing data collection. The second phase starts by input the data and do analysis for the data obtained. Classification for the data is also done in this phase where the data classified according to the fault. Lastly, the third phase is where a graphic user interface is designed using MATLAB. The output of the graphic user interface will prompt the user about the fault that has been detected from the data imported. Discussion of the fault will be followed up by then when the classification is complete.

C. Graphic User Interface

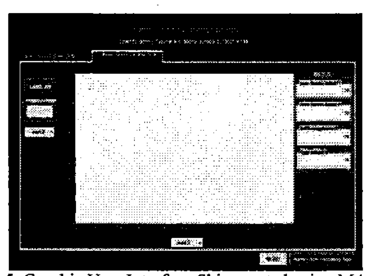
Figure 5. Graphic User Interface Skin created using MATLAB

Figure 5 is the graphic user interface created using MATLAB. It is very user friendly. The GUI consists of two tabs where one for speed from 48-600 rpm and the second one are ranging from 600-3600rpm. User will be required to import the excel file by pushing the load file button. For more information about import excel file can be found on the help menu provided. After importing excel file, user will required to key in the range of frequency user want to plot. Then select the y-axis to 'data' and the graph will appear at the axes. The right corner panel there will prompt the user the status of the data obtained. There is also a reset button for user to reset all the things.

IV. EXPERIMENT

There are two types of bearings in this experiment. One is single angular row contact ball bearing and the other one is self-aligning ball bearing. Figure 6 shows the flow of the experiment. The experiment starts with fixing an accelerometer to the bearing housing. Then by using a Real Time Frequency Analyzer (RTFA), the data is collected. It is then transfer to the computer by using a data acquisition card. Hence, from the computer, the data is inputted into the graphic user interface created using MATLAB. Lastly, the result of Fast Fourier Transform is shown in the graphic user interface and also the classification of the data defects.

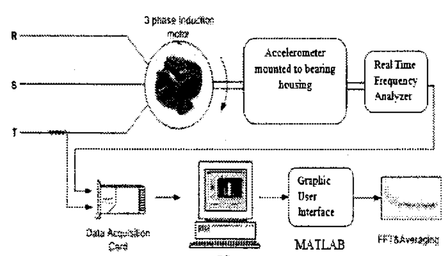

Figure 6. Flow of the Experiment

A. Single Angular Row Contact Ball Bearing

A.1 Model

Figure 7. Single Angular Row Contact Ball Bearing Experiment

Figure 7 shows the experiment conducted using the machine model above to conduct the experiment. The red circle this is the place where the accelerometer is mounted and collect the data. The measurement of the bearing is as below:

Number of balls = 8
Ball Diameter = 0.01m
Pitch Diameter = 0.05m
Contact Angle = 40°
Speed of motor = 2400 rpm

A.2 Experiment Technique

The experiment start using an accelerometer to mount on the red circle that is equipment that mounts to the housing of the bearing. The placement of the accelerometer sensors in very important as it plays a very important role that is to collect every data produced by the bearing. In this measurement, 6 sets of data are collected from the six different bearings in the machine model. The data are taken using a real time frequency analyzer with an accelerometer connected to it. The data collected which will then be transferred to a computer and read using CMS software. Then the data will further analyze by spectral analysis using Fast Fourier Transform in MATLAB.

B. Self Aligning Ball Bearing

B.1 Model

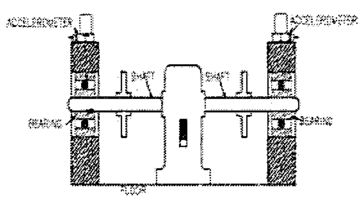

Figure 8. Rig Model for Self Aligning Ball Bearing

Figure 8 shows how the experiment for self-aligning ball bearing is conducted.

Number of balls = 24
Ball Diameter = 0.004m
Pitch Diameter = 0.05m
Contact Angle = 15°
Speed of motor = 2200 rpm

B.2 Experiment Technique

The experiment technique is same as the single row angular contact bearing. The only difference is the motor used and the bearing mounting position. Besides that, for this self aligning bearing, 8 datas are collected for comparison.

V. CASE STUDY

Refer to Figure 7, that is a model tested for single angular row contact ball bearing. There are 6 bearings that some of them consist some specific defect on it which is for experiment used. Table 1 shows the bearing number and also the designed defect on it.

TABLE I
BEARING NUMBER AND TYPE OF DEFECT

Bearing Number	Type of Defect
3	No Defect
4	No Defect
5	No Defect
6	Inner Raceway Defect
7	Outer Raceway Defect
8	Inner Raceway Defect

The data obtained using accelerometer are plotted using Fast Fourier Transform to have a comparison with the built in defect. The frequency range of 500 Hz is used to have a better overview for the amplitude obtained.

A.1 Bearing 3

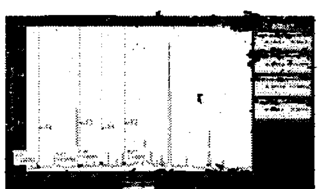

Figure 9. Bearing Number 3 Fast Fourier Transform Graph (f = 500Hz)

Figure 9 shows the graph plotted for bearing number 3. Since the built in bearing is a healthy bearing, therefore from the graph plotted from the data obtained clearly shows that there are no defect at all for this bearing where all the fault frequency amplitude is below 0.05.

A.2 Bearing 4

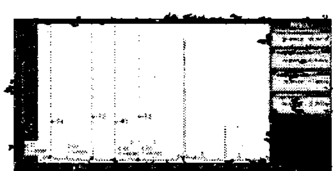

Figure 10. Bearing Number 4 Fast Fourier Transform Graph (f = 500Hz)

Figure 10 shows the graph plotted for bearing number 4. Bearing in the experiment model is a healthy bearing where no defect on it. Therefore, from the graph plotted from the data obtained, it shows that no defect detected at all at the results panel at the top right corner. All the fault frequency amplitude is below 0.05.

A.3 Bearing 5

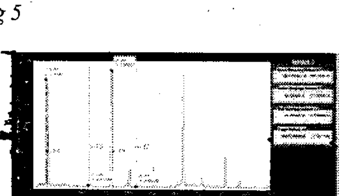

Figure 11. Bearing Number 5 Fast Fourier Transform Graph (f = 500Hz)

Figure 11 shows the graph plotted for bearing number 5. It suppose to be a healthy and no defect bearing, however the graph plotted from the data obtained shows that the vibration amplitude exceed the alert state for inner raceway and cage frequency. The amplitude for the inner raceway frequency is 0.05532 and cage frequency is 0.051.

A.4 Bearing 6

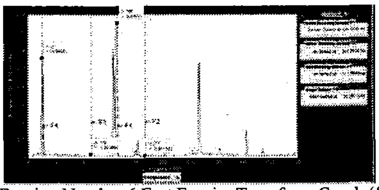

Figure 12. Bearing Number 6 Fast Fourier Transform Graph (f = 500Hz)

Figure 12 shows the graph plotted for bearing 6. Initially, bearing 6 is a inner raceway defect bearing. The graph plotted shows that there is 1 danger defect and 1 alert defect. The danger defect is at inner raceway frequency which amplitude is 0.07533 while cage defect amplitude is at 0.05563. This shows that beside inner raceway defect, the cage of the bearing also have some small defect on it.

A.5 Bearing 7

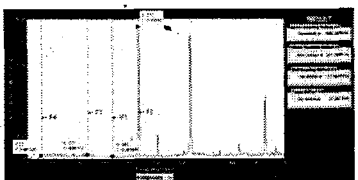

Figure 13. Bearing Number 7 Fast Fourier Transform Graph (f = 500Hz)

Figure 13 shows the graph plotted for bearing number 6. Bearing number 6 is a built in outer raceway defect bearing and from the graph plotted obtained also, it clearly indicates that there is an alert defect detected at outer raceway frequency where its vibration amplitude exceed 0.05 which is 0.05644.

A.6 Bearing 8

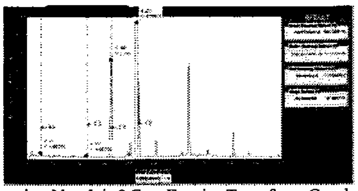

Figure 14. Bearing Number 8 Fast Fourier Transform Graph (f = 500Hz)

Figure 14 shows that the graph plotted for bearing number 8 with the data obtained from accelerometer. Bearing number 8 suppose to have an inner raceway defect on it. From the graph, it shows that the data obtained have inner raceway defect and also the outer raceway defect at the same time. The vibration amplitude for inner raceway defect is 0.056 and for outer raceway defect is at 0.07655.

TABLE II

COMPARISON FOR DESIGNED DEFECT AND DETECTED DEFECT

Bearing Number	Designed Defect	Detected Defect
3	No Defect	No Defect
4	No Defect	No Defect
5	No Defect	Alert Inner Raceway Defect and Alert Cage Defect
6	Inner Raceway Defect	Danger Inner Raceway Defect and Alert Cage Defect
7	Outer Raceway Defect	Outer Raceway Defect
8	Inner Raceway Defect	Alert Inner Raceway Defect and Danger Outer Raceway Defect

The comparison table II is the summary for the built in defect for the bearing and also the detected bearing defects.

Some of the bearing data obtained exhibit exactly like the one designed for the experiment and some are not. Those who have the same results are bearing number 3, 4 and 7, whereas for those have extra defect detected instead only the designed defect are bearing 5, 6 and 8. From what it might cause for the extra defect detected is the time constrain for the bearing itself and also the bearing lifespan. The machine model have been bought more than 6 years, therefore, they might be some defect occurred along all these years and cause the extra detection.

VI. ANALYSIS & DISCUSSION

A. Analysis

The vibration spectrum has a close relationship with the condition of the machine. Any failure in the bearing will be affected by increasing the vibration amplitude that makes the machine sounds louder and harder. For certain cases, good bearing will have their own spectrum shapes, so do bad bearings. When the faults begin to develop, the vibration spectrum amplitude changes. This is because the force acting onto the bearing has changed during the dynamic process in the machine due to the defects on the bearing. The data collected is only up to 1600Hz that is enough to detect all the bearing defects. There are several defects of bearing such as inner race defect, outer race defect, ball bearing defect and also bearing cage defect [1].

A.1 Single Angular Row Contact Ball Bearing

Table III shows the measurement and calculation for single angular row contact ball bearing.

TABLE III

SINGLE ANGULAR ROW CONTACT BALL BEARING MEASUREMENT

N=8	B=0.01m	P=0.05m	θ=40°	RPM=2400
$BPFO = \frac{8}{2}(1 - \left(\frac{0.01}{0.05} x \cos(40)\right) x \frac{2400}{50} = 217.61\text{Hz}$				
$BPFI = \frac{8}{2}(1 + \left(\frac{0.01}{0.05} x \cos(40)\right) x \frac{2400}{50} = 166.39\text{Hz}$				
$BSF = \frac{0.05}{2(0.01)}(1 - \left((\frac{0.01}{0.05})^2 x \cos(40)^2\right) x \frac{2400}{50} = 117.86\text{Hz}$				
$FTF = \frac{1}{2}(1 - \left(\frac{0.01}{0.05} x \cos(40)\right) x \frac{2400}{50} = 27.20\text{Hz}$				

A.1.1 No defect Single Angular Row Contact Ball Bearing

For the particular defects frequency, there are certain standard of amplitude provided by ROCKWELL AUTOMATION. According to them, when the amplitude of the frequency exceeds 0.05, it shows that the bearing is no more than a good bearing where it starts to have defects. Then, when it exceeds 0.075, the user must be alerted that the bearing is at a dangerous condition where the user must not use the bearing anymore. Below is the Fast Fourier transform (FFT) graph plot using the data obtained from mounting the accelerometer to get the acceleration amplitude.

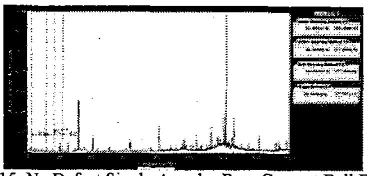

Figure 15. No Defect Single Angular Row Contact Ball Bearing (f=1600Hz)

Figure 15 is the Fast Fourier Transform graph plotted for a good bearing for a frequency range of 1600Hz. From the vertical red dotted line, it shows that each different fault have its own frequency. When the acceleration amplitude at the particular frequency did not exceed the limit, it is says to be a good bearing that is without defects. At the top right corner there are the results of the FFT graph above, when the results is written in black colour, it means no defects occurred at the particular frequency.

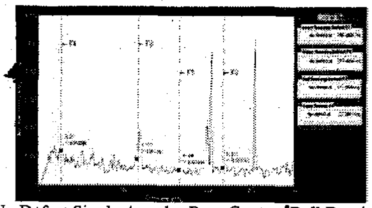

Figure 16. No Defect Single Angular Row Contact Ball Bearing (f=300Hz)

Figure 16 shows the same bearing with no defect, but the plotted frequency has been reduced to 300Hz. This can give a better overview for the FFT graph where it can clearly shown that, the amplitudes of the fault frequencies did not exceed the minimum height for the standard that have being set. Therefore, no defects detected for this bearing.

A.1.2 Defect Single Angular Row Contact Ball Bearing

Whenever there is an increase in amplitude in the graph, it shows that there will be a defect. Different particular frequencies will shows different type of defects. The entire bearing graph is plotted for only 300 Hz because all the fault frequencies are below 300Hz.

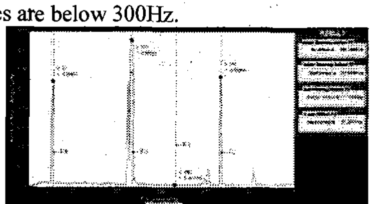

Figure 17. Defect Single Angular Row Contact Ball Bearing (f=300Hz)

Figure 17 shows one of the defects ball bearings. From the results obtained from the FFT graph, it shows that there are three defects which are outer race bearing defect, ball bearing defect and also cage defect. The acceleration amplitude for ball bearing frequency is at 0.07533. While outer race bearing and cage defect is at alert level. At the top right corner there clearly shown the results of the bearing defects.

A.2 Self Aligning Ball Bearing

Table IV shows the measurement and calculation for self-aligning ball bearing.

TABLE IV

SELF-ALIGNING BALL BEARING MEASUREMENT

N=24	B=0.004m	P=0.05m	θ=15°	RPM=2200
$BPFO = \frac{24}{2}(1 - \left(\frac{0.004}{0.05} x \cos(15)\right) x \frac{2200}{50}$ = 560.08Hz				
$BPFI = \frac{24}{2}(1 + \left(\frac{0.004}{0.05} x \cos(15)\right) x \frac{2200}{50}$ = 495.91Hz				
$BSF = \frac{0.05}{2(0.004)}(1 - \left((\frac{0.004}{0.05})^2 x \cos(15)^2\right) x \frac{2200}{50}$ =117.86Hz				
$FTF = \frac{1}{2}(1 - \left(\frac{0.004}{0.05} x \cos(15)\right) x \frac{2200}{50}$ = 23.34Hz				

A.2.1 No defect Self Aligning Ball Bearing

This is another type of ball bearing which has two columns of ball bearing which are stick together to form a bearing. The standardization acceleration amplitude is the same as the ball bearing type which is alert state from 0.05 to 0.075 and dangerous state for those who exceeds 0.075. Below is the Fast Fourier Transform graph plotted using the data obtained from the accelerometer.

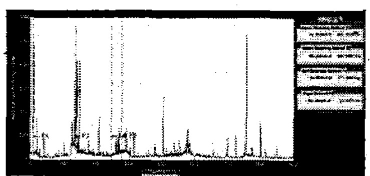

Figure 18. No defect Self Aligning Ball Bearing (f=1600Hz)

Figure 18 shows the Fast Fourier Transform graph plotted for a good bearing for a frequency range of 1600Hz. The red vertical dotted line there used to indicate the defects frequency points. This is a good bearing where the acceleration amplitude for the bearing defect frequencies does not exceed the limit. The top right corner panels will shows the user the state of each defects and the frequency of defects by referring to the FFT graph plotted.

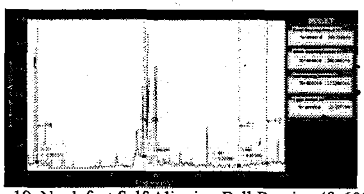

Figure 19. No defect Self Aligning Ball Bearing (f=600Hz)

Figure 19 shows the no defect bearing plotted for the range of 600 Hz. From the data shown in the graph, it clearly shows that no amplitudes out of four defect frequencies exceed the alert state limit.

A.2.2 Defect Self Aligning Ball Bearing

A defect occurred when there is an increase in acceleration amplitude at the particular frequencies. Below are the data that can indicate the bearing defects accurately.

Figure 20 below shows the wear self-aligning bearing. The defects detected are inner race defect, outer race defect and cage defect. The amplitude for inner race is 0.06522, outer race is 0.05022 and cage defect is at 0.05634. All the defects amplitude is below dangerous level 0.075 Therefore the top right panel indicates the defects correctly.

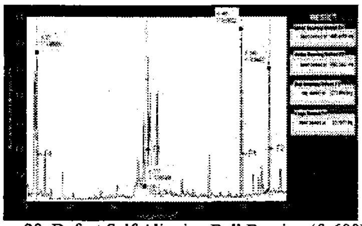

Figure 20. Defect Self Aligning Ball Bearing (f=600Hz)

B. Discussion

Bearing wear is one of the most frequent happens fault in industrial. Bearing failure is usually progressive but ultimately its effect upon the machine is catastrophic. Failure is accompanied by a rising in amplitude at the bearing housing which is detectable using an accelerometer. An important event that will cause the amplitude to increase is the rotor becomes eccentric in the stator bore causing a degree of static and adjacent poles, which causing unbalanced magnetic pulled where it will placed more load on the bearing. This eventually caused an increase in vibration as the shaft dynamics are affected by altered air gap and bearing stiffness [23]. Besides that, there are still a number of mechanisms that can lead to bearing failure, including mechanical damage, crack damage, wear damage, lubricant deficiency and corrosion. Other than that, abusive handling can induce nicks and dents that are especially harmful when located in areas tracked by the rolling elements. Higher stress conditions imposed on the surface will reduced the bearing life significantly when the smooth rolling contact surfaces are marred. Permanent indentation created by rolling element overload is called brinelling. Crack in bearing component can be induced by operating stress via overload or cyclic loading [1].

VII. CONCLUSIONS

All in all, this project had achieved the objectives, which are to measure the wear bearing without dissembling the bearing out and to predict the condition and shutdown possibility occurred by using Fast Fourier Transform spectral analysis. The results of the investigation show that, during bearing wear, there is an increase in vibration acceleration amplitude of machine running. Therefore, by monitoring at the vibration amplitude, the condition of the bearing and motor breakdown can be determined and control. Besides that, monitoring vibration acceleration amplitude using Fast Fourier Transform is a very good practice for this research where every single fault frequencies can be shown nicely from the graph plotted. Moreover, with the help of MATLAB GUI, further interpretation and analysis was possible from the data collected. The graphic user interface had been compiled which made it can be used by user who do not have MATLAB in their computer.

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