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Fault Diagnosis and Simulation of Rolling Element Bearing Using Condition Monitoring

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ABSTRACT

Rolling element bearings find widespread domestic and industrial application as it is an important factor in failure of rotating machines and therefore bearings are the one which are exposed the most towards getting damaged and failure. In industrial applications, these bearings are considered as a critical mechanical components and a defect in such a bearing, unless detected in time, causes malfunction and may even lead to catastrophic failure of machinery which results in significant time and economic loss. These types of failures might take place during the manufacturing process and therefore it is important to review the problem and monitor the condition of roller bearings so that an early detection and indication is necessary for the safety and reliability of monitoring techniques suitable to analyze the defect This paper focuses conditioning monitoring tech. vibration analysis and acoustic analysis methods . An experimental set up is used to testify and investigate good bearing and faulty bearing by using different measurement tools pulse software, visteck analyzer to measure amplitude, sensors to obtain faulty signals and computer oriented programming software MATLAB for finding faulty frequencies at inner race.

Keywords— Acoustic analysis, Matlab, Roller bearing diagnosis, Vibration analysis.

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I.INTRODUCTION

1.1.1 Background:

In 21st century, managing the industries has become one of the challenging tasks due to change in management structure, increased global competition, intense change in technology, reliability, health and safety, consumer demands towards quality and environmental considerations [9]. Taking into consideration all the above factors there is great chance to improve the opportunities as well as strategic plans and therefore make the most benefits of the modern manufacturing techniques and methods. Advanced manufacturing methods and techniques, quality of human resources has greatly persuaded the productivity in manufacturing industry. [9] Manufacturing companies in the India pay out three times as much every year in replacing the machinery and maintaining the existing plant. As there have been several sectors in manufacturing affected by the different issues related with the rotating machineries, one of the major issues in the manufacturing has been early detection of faults which has result in the unplanned breakdowns, maintenance cost and so it has been disaster failure in machinery or process [7]. To overcome and therefore prevent these failures, different techniques of maintenance management like corrective maintenance, breakdown maintenance, preventive maintenance, time based maintenance and condition based maintenance are widely utilized [15]. All these techniques are viable in some and the other way for the different failure machinery for manufacturing industry. Above all, condition based maintenance is one of the best method in early detection of faults in rolling element bearing. Usually these faults in the rolling bearing element occurs due to corrosion, overheating, excessive load, lubrication failure, misalignment, tight fits, normal fatigue failure and contamination.

1.1.2 Vibration Analysis

Vibration analysis is most powerful tool for fault diagnosis of bearing. Accuracy of operation of bearing is related with elements like housing, shafts and nuts. Some of the bearings fail earlier in service because of the poor lubrication, tight fitting, loose fitting, contamination and misalignment.

Acoustic analysis

Acoustic analyzer captures the sound waves and analyze, this analysis helps to find the leakage faults, detection of crack and another bearing defects. Acoustic analysis is cost effective and less complicated technique of CM. Sound from bearing is usually complex and its combination of many sinusoidal waves which provides the exact fault information. Tools like vistec (amplitude meter), pulse software, different sensors, acoustic analyzer and more are used to measure the different parameter produce from the rolling element bearing. [10] these tools are used to obtain time domain and frequency domain of the different vibration signals. High frequency signals in the range 100-150 kHz. Regular mechanical bearing vibrations do not exceeds 30 kHz and impact waves arising in a faulty bearing frequency are reaching 50 kHz and more [8]. Acoustic analyser captures the sound waves and analyse, this analysis helps to find the leakage faults, detection of crack and another bearing defects.

1.1.4 Characteristic frequencies of the bearing:

The vibration analysis technique gives the precise and early information about the failure of bearing. According to Tondon and Choudhary [12] faults in bearing (inner race, outer race and cage fault) produces the particular defective frequencies which is calculated by using the following equations.

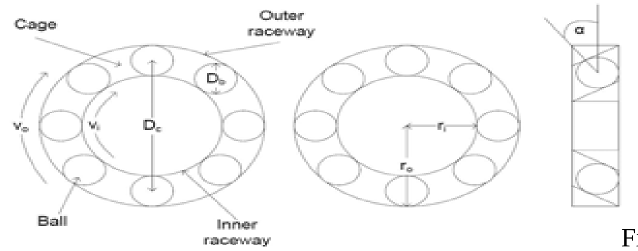


Figure1.1.1:Standard rolling-element bearing

Ball Pass Frequency at inner race of bearing (BPFi)

BPFi=fr*(1+(d/D)*cos(A))*B/2..................-------1

Ball Pass Frequency at inner race of bearing (BPFo)

BPFo=fr*(1(d/D)*cos(A))*B/2...................--------2

Cage malfunction frequency

FTF=fr/2*(1+(d/D)*cos(A))........................---------3

Ball Spin Frequency

(BSF)=fr*(1(d^2/D^2)*(cos(A))^2)*d/(D*2).......-4

Where,

fr=running frequency, n = no of balls

d = roller diameter , D = pitch diameter

A = contact angle , N = revolution/ minute

These equations are based on the good rolling races; nonetheless practically additional sliding motion might cause changes in characteristic frequencies.

ConditionMonitoring

[4] Conditioning monitoring mostly focuses on the vibration data including sample of lubricant, temperature readings and measurement of shocks from rolling element bearing defects.[2] conditioning monitoring as "conditioning monitoring on or off-line is a type of maintenance inspection where an operational asset is monitored and the data obtained analyzed to detect signs of degradation, diagnose cause of faults, and predict for how long it can be safely or economically run". There are several benefits of conditioning monitoring which potentially affects on the improved productivity, maintenance cost and increased plant availability. [9] The following methods are generally used for condition monitoring of the bearings:

- Vibration analysis ,Oil debris analysis
- Acoustic analysis , Visual inspection
- Corrosion analysis

Some of the important and majorly used measurement techniques within the conditioning monitoring are as follows:

II.ACOUSTIC ANALYSIS

The sound vibration is generated from the bearings due to application of the physical energy. The signals used are acoustic air particles and sound pressure. These signals facilitate to analyse the fault in bearing. Frequency peaks plotted using the acoustic analyser..

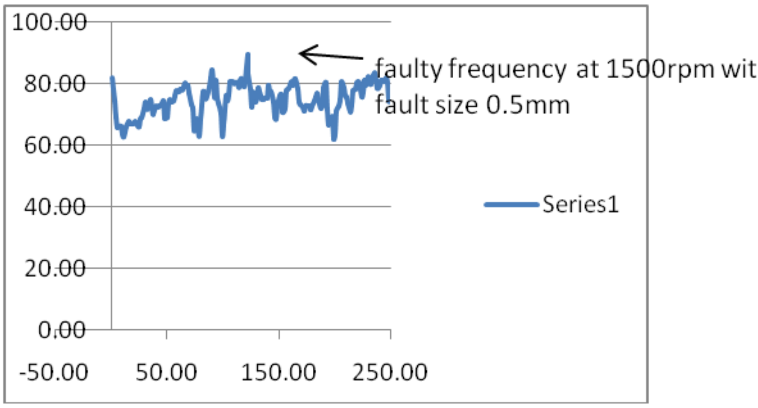


Figure 1.1.2: Typical acoustic signal of faulty bearing

Acoustic analysis is cost effective and less complicated technique of conditioning monitoring. Comparison between good bearing and faulty bearing frequencies are analyzed using acoustic analysis and pulse software. These results were verified using MATLAB simulation.

- Vibration analysis: [9] Vibration analysis is the most tangible and established technique in conditioning monitoring. [8] Vibration analysis has been used comprehensively in diagnosis of bearing in rotating machine. Like most of the other techniques, where we need to shutdown the equipment to detect the problems, vibration analysis don't require to shutdown the equipment and so it can be performed on line by computer based machine monitoring system.[5]To identify the faults of bearings, the received vibrating signals are processed by different methods.

[7] These methods are traditionally been used either in terms of time domain or frequency domain. These techniques are broadly classified as follows:

- Time domain analysis.
- Frequency domain analysis.
- Combined time-frequency domain analysis.

1.2.3Timedomainanalysis

The time domain analysis is nothing but display or analysis of the vibration data as a function of time. To detect the fault, the time domain method analyzes phase information and amplitude of the vibration time signals [14]. Changes in vibration signals due to faults were detected by studying the time domain waveform using equipments like vibrographs, oscilloscope or oscillographs.[14] The time domain analysis focuses principally on statistical characteristics of vibration signals such as: Standard deviation., Peak level., Skewness., Kurtosis.,Crestfactor. To detect the faults at the bearing, the differences of phase and vibration amplitude due to damage of components are used. [8] Time domain analysis can be used to identify the damage occurring in bearings such as cracks on outer and inner races. In addition to diagnose the fault of bearing, kurtosis of phase modulation and its derivatives are used.

1.2.4 Frequency domain analysis

Frequency domain analysis is the classical bearing diagnostic technique also known as spectral analysis. [7] Frequency domain analysis method is more reliable and most sensitive than time domain analysis method. The vibration data is analyzed as a function of frequency by frequency domain analysis. The spectrum of faulty bearing and the bearing in good condition is compared and its difference is used in detecting faults on bearing [12]. Obtaining narrowband spectra easily and more efficiently is mostly done by using Fast Fourier Transform (FFT). Fast Fourier transform algorithm is used to process time domain vibration signal into frequency domain. In other words, frequency spectrum is achieved as frequency domain method mainly uses numerical fast Fourier transform to the vibration signal. There are different methods of frequency domain vibration signature analysis which are as follows:

- Shock pulse
- Enveloped spectrum.
- Signature spectrum.
- Band- pass analysis.
- Cascades.

1.2.5 Computer oriented programming for vibration analysis (MATLAB)

Matlab is a fourth generation programming language and is kind of software programming or it is kind of a system which is usually used for numerical computation. It usually help in lowering down a routine tasks associated with numerical problem solving, which ultimately allows to spend more time in thinking and giving more time to discover the experiment.. It is so easy and functional that even big operations can be carried out using couple of commands. One can build its own set of functions for particular application. Matlab provides excellent graphic facilities and therefore it is widely used in vibration analysis.

III. METHODOLOGY

1.3.1 Experimental Setup:

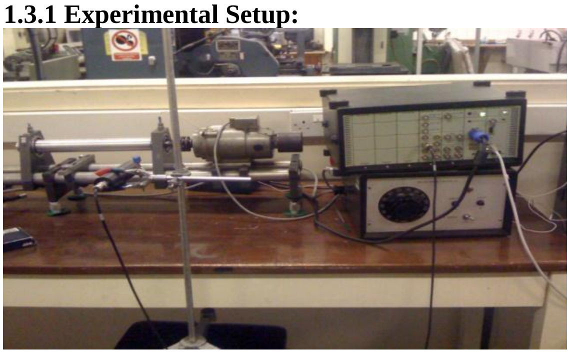


Figure1.3.1: Experimental Set-up

The vibrations produced by the bearing, changes as the fault starts to develop. In this practical experimentation, the vibrating signals produced from faulty bearings and good bearings were compared to diagnose the faulty frequencies. The assembly consists of two bearing at the end of bearing housing. The shaft has been inserted in housing. Photo electric tachometer is used to calculate the speed of the bearing. Vistec hand held tool is used to measure the amplitude produced across the bearing.

1.3.2Photo Electric Tachometer 1.3.3Vistec hand held tool

1.3.4 Acoustic Analyzer

With help of acoustic analyzer sound waves have been captured and data will get interpreted on excel sheet faulty frequencies Vs sound level in Db. This is most remarkable method which consumes less time and cost.

Under various conditions of good and faulty bearings following data was collected. Faulty frequencies were observed using both FFT analyzer and Acoustic analyzer at the same time, also effect of speed on amplitude and sound level were evaluated. MATLAB software was used to calculate the faulty frequencies at inner race and to filter the noisy signals. On the basis of bearing characteristic frequency equation, ball pass frequencies at inner race were calculated. The features of the signals like amplitude values, sound level, peak to peak and RMS were recorded at different fault size at different speeds for comparison. The following methods were used for fault diagnosis of the bearing:

- Fast Fourier Transform (FFT) Analysis:
- Acoustic Emission Analysis:
- Spectrum analysis of vibration signals:

1.3.2 Fast Fourier Transform (FFT) Analysis:

FFT perceived the fault frequencies occurred due to vibration of the bearing. By using the following equation of bearing characteristic fault frequency at inner race, theoretical fault frequencies at different speed were calculated by using MATLAB programming.

$BPFi= (1+ (d/D)*\cos (A))*B*N/2$

Where,

B = no of balls

d = roller diameter

D = pitch diameter

A = contact angle

N = revolution/ minute

Specifications of the bearings used for experiment,

Roller diameter (d) =11mm
Pitch diameter (D) =51mm
Contact Angle (A) =0
Number of ball bearings (B) =8
In order to calculate the harmonics of the running speed, it is necessary to calculate the side band frequency.
a) For N=2400rpm, BPFi = 197.37Hz
Side band frequency f = N/60 = 40 Hz
Harmonics of running speed:
1 * rpm = 1 * 40 = 40 Hz, 2 * rpm = 2 * 40 = 80 Hz, 3 * rpm = 3 * 40 = 120 Hz
b) For N=1500rpm, BPFi = 123.35 Hz
Side band frequency f = N/60 = 25 Hz
Harmonics of the running speed:
1 * rpm = 1 * 25= 25 Hz, 2 * rpm = 2 * 25 = 50 Hz, 3 * rpm = 3 * 25 = 75 Hz
c) For N=1800rpm, BPFi = 148.02Hz
Side band frequency f = N/60 = 30 Hz
Harmonics of running speed:
1 * rpm = 1 * 30 = 30 Hz, 2 * rpm = 2 * 30 = 60 Hz, 3 * rpm = 3 * 30 = 90 Hz

It was found that at different harmonics of the running speed vibration spectrum produces peaks. Bearing produces vibration spectrum for its specific frequency. According to Botsaris and Koulouriotis [5] harmonics are generated due to bearing clearance, small unbalance and non-linearity of the machine. Specific frequency components facilitate to evaluate the bearing condition. The linear function of number of the balls and the running speed in bearing derives bearing inner race faulty frequencies. Due to internal preloads and thrust loads on the bearing, the quantified values for the characteristic frequencies might or might not exactly match the theoretical one. Signals from the pulse software and acoustic analyser were observed and verified by using MATLAB.

IV. RESULTS AND DISCUSSION

1.4.1 FFT and Matlab Analysis:

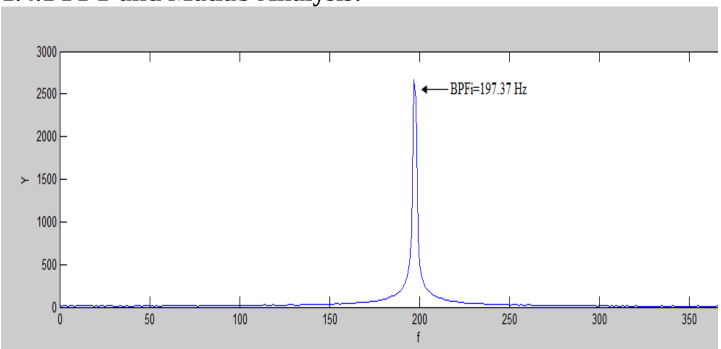


Figure 1.4.1 Theoretical frequency with fault size 0.5mm at speed 2400rpm calculated using MATLAB.

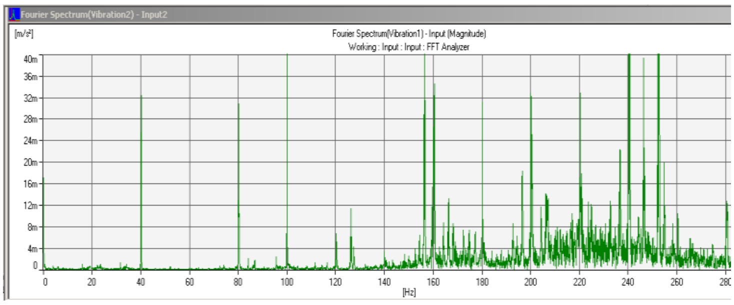


Figure 1.4.2 A typical observed signal for an inner race fault 0.5 mm rotating at 2400 rpm and amplitude 0.161

From the above figure 1.4.2 it can be seen that at speed 2400 rpm bearing with fault size 0.5mm produced the strong peak near 200 Hz. This frequency more or less matches with the characteristic frequency i.e. BPFi=123.35 Hz (figure 1.4.1) which is calculated by using MATLAB programming. This shows that a strong peak provides information about the fault of the bearing. There might be 10% variance in the results. Strong peak indicates that there is a fault at inner race of the bearing.

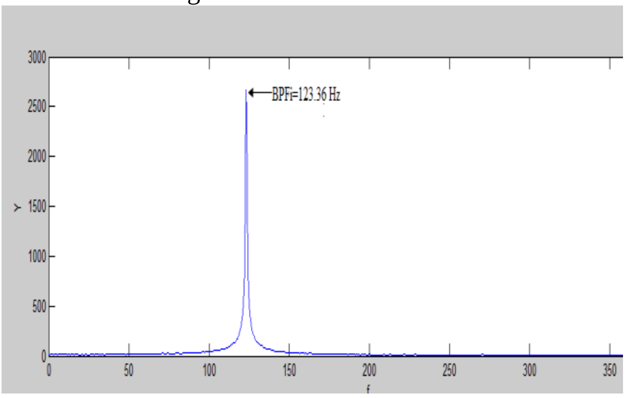


Figure 1.4.3 Ball pass frequency of bearing with fault size 1mm at 1500rpm using MATLAB

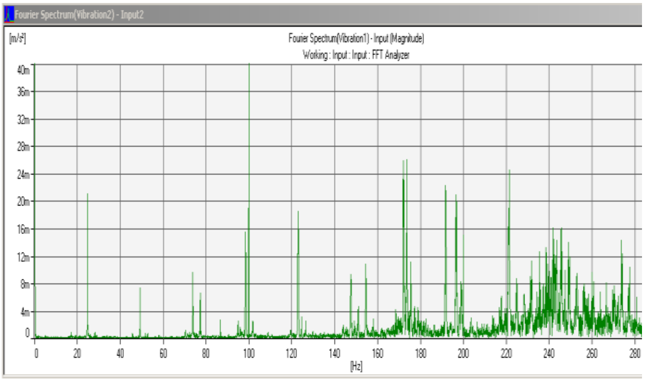


Figure 1.4.4 A typical observed signal for an inner race fault 1mm rotating at 1500 rpm and amplitude 0.045

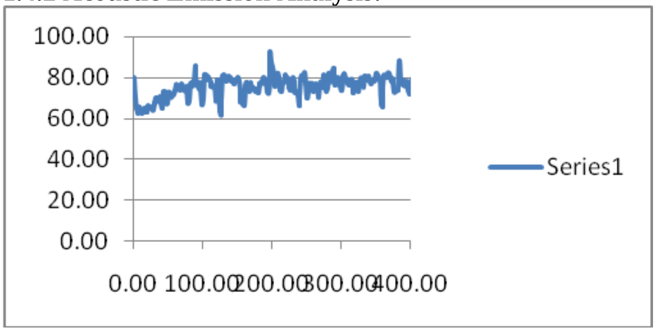
From the above figure 1.4.4 it can be seen that at speed 1500 rpm and fault size with 1mm produces the strong peak near 124 Hz. This frequency more or less matches with the characteristic frequency i.e.(BPFi=123.36 Hz) figure 1.4.3 which is calculated by using MATLAB programming. This shows that a strong peak provides information about the fault of the bearing. There might be 10% variance in the results. There is strong peak so it is observed that fault is at inner race of the bearing.

For faulty bearings some peaks were generated at the frequencies corresponding to the harmonics of the running speed whose respective values closely matches with the theoretical frequencies. The following table shows the results at different speeds.

Speed(rpm)		Theoretical Frequency(Hz)	Experimental Frequency(Hz)
1500	1*rpm	25	25
	2*rpm	50	49
	3*rpm	75	76
1800	1*rpm	30	30
	2*rpm	60	60
	3*rpm	90	90
2400	1*rpm	40	40
	2*rpm	80	80
	3*rpm	120	120

Table 1.4.1 Calculated theoretical & experimental frequencies of harmonics of running speeds

1.4.2 Acoustic Emission Analysis:



Speed (N) (rpm)	Theoretical Inner race faulty freq. BPFi (Hz)	Experimental Fault freq. using FFT(Hz)	Experimental Fault freq. using Acoustic analyzer(Hz)	Amplitude measurement (mm)	Sound level in(Db)
1134	93.25	94	92.30	0.034	87.24
1500	123.35	124	123.56	0.045	90.12
1800	148.02	152	147.90	0.054	91.24
2400	197.37	201	196.30	0.14	93.56

Figure 1.4.5 typical signal of bearing with fault size 0.5mm at speed 2400rpm captured by acoustic analyzer .Strong peak was produced at 196.03Hz by acoustic emission signal which can be seen in figure 1.4.5. This result was compared with the FFT and MATLAB results with same size fault and at same speed. It can be concluded that, acoustic analyzer also produces the strong peak at bearing characteristics frequency at inner race. Peaks obtained from acoustic readings were not uniform and that might be because of environmental sound which affects the results. It also shows that, bearing releases the vibration energy from the defect which produces effect on acoustic signal resealed in the maximum frequency range.

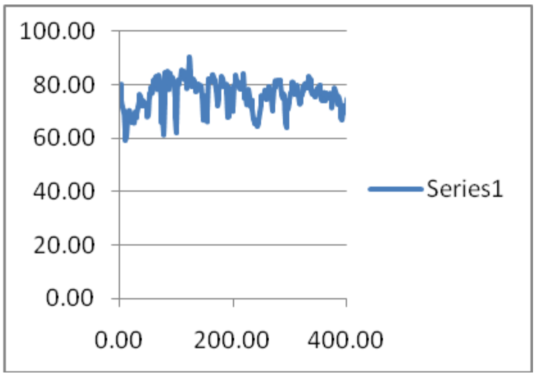


Figure 1.4.6: typical signal of bearing with fault size 1mm at speed 1500 rpm captured by acoustic analyzer. Strong peak was produced at 123.56Hz by acoustic emission signal which can be seen in figure 1.4.6. This result was compared with the FFT and
Table 1.4.3: Experimental readings with bearing fault
MATLAB results with same size fault and at same speed. It can be concluded that, acoustic analyzer also produces the strong peak at bearing characteristics frequency at inner race. Same results were obtained with bearing with fault size 0.5mm. 1mm and 1.5mm at inner race rotating at 1134rpm, 1500rpm,1800 and 2400rpm.
The following table 1.4.2, 1.4.3 and 1.4.4 gives clear idea about the experimental results at different speed. The theoretical fault frequencies at inner race were calculated by using MATLAB programming which gives good results, as those results are almost matching with the pulse software and acoustic emission. That means one can use the MATLAB programming as a supporting tool for bearing fault detection.

Speed (N) (rpm)	Theo Inner race faulty freq. BPFi (Hz)	Experimental Fault freq. using FFT(Hz)	Experimental Fault freq. using Acoustic analyzer (Hz)	Amplitude measurement (mm)	Sound level in(Db)
1134	93.25	95	93.80	0.039	86.24
1500	123.35	123	122.60	0.058	89.53
1800	148.02	152	149.40	0.074	91.16
2400	197.37	201	196.03	0.161	92.48

Table 1.4.2: Experimental readings with bearing fault size 0.5mm at different speed

Speed (N) (rpm)	Theoretical Inner race faulty freq. BPFi	Experimental Fault freq. using FFT (Hz)	Experimental Fault freq. using Acoustic analyzer (Hz)	Amplitude measurement(mm)
1134	93.25	94	89.40	0.039
1500	123.35	124	120.10	0.051
1800	148.02	152	145.00	0.059
2400	197.37	201	193.40	0.117

Table 1.4.4: Experimental readings with bearing fault size 1.5mm at different speeds

By using above tabular information the following graphs were plotted, in order to analyze the different conditions of the bearing.

- Speed (rpm) Vs Amplitude (mm)

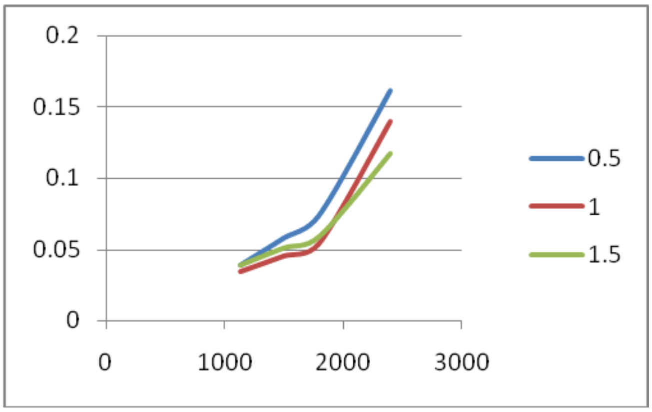


Figure 1.4.7: Speed Vs Amplitude of different size of faulty bearings

The above figure indicates that, as speed increases the amplitude also increases. So it can be concluded that speed is directly proportional to the amplitude.

- **Speed (rpm) Vs Sound Level (Db)**

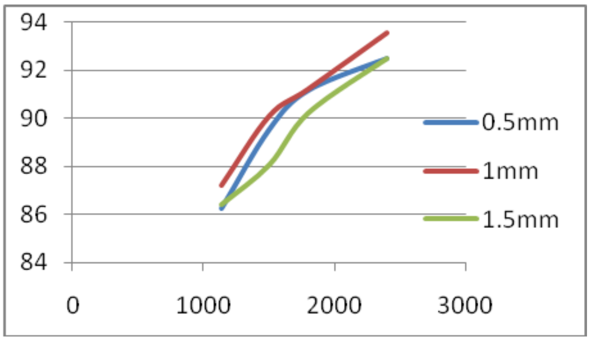


Figure 1.4.8: Speed Vs Sound Level of different size of faulty bearings.

The above figure indicates that, as speed increases the intensity of sound level in Db also increases. The sound level values were taken where the strong peak occurred. Therefore, it can be concluded that speed is directly proportional to the sound level. Thus irregularities in surface produces the noise level in the rolling contact which increases as number of irregularities in surface increases. This pressure of sound helps to measure the acoustic signal generated by the bearing.

- **Faulty frequencies Vs Amplitude**

The distribution of defects coincides due to localized defects and so many frequencies produced. It is difficult to find the information of the single frequency. To minimise the complication, amplitude of the frequency spectrum components must be considered for defective bearing.

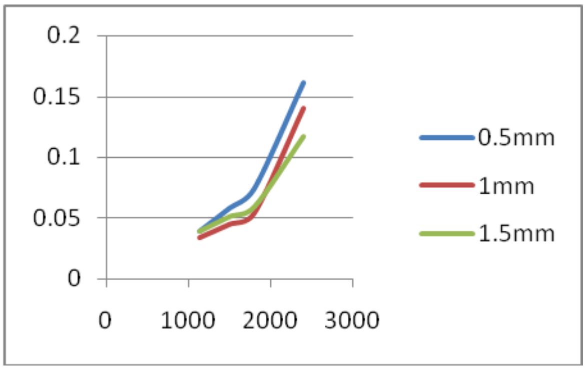


Figure 1.4.9: Faulty frequencies Vs Amplitude of different size of faulty bearings

The above figure indicates that, as Faulty frequency at inner race increases the vibration level increases which result in increase in amplitude. Therefore, it can be concluding that Faulty frequency is directly proportional to the amplitude.

V. CONCLUSION

Early detection of faults has been one of the major issues in the manufacturing industries. In recent years, the industry has been evolved from the costly time based maintenance schedules to more efficient condition based maintenance. With help of Fast Fourier Transform, acoustic analysis and the calculation of spectrum of frequencies, the frequencies of element bearings can be differentiated and conceived if there is any fault present in particular component so that the interruption of machine operation can take place on times. Different signal data were obtained for good new bearings and faulty bearings with induced inner race faults at 0.5mm, 1mm and 1.5mm. Each of the bearing was tested for 1134 rpm, 1500rpm, 1800rpm and 2400rpm. In the data analysis, plots obtained for each test conditions are compared i.e. different frequencies obtained from Fast Fourier Transform (FFT) analyzer and acoustic analyzer were compared. The theoretical Vibration fault signatures were also compared with the frequency determined from power spectrum graphs and frequency domain graphs. The faults acquired from the MATLAB programming were compared with the measured ones from both the analysis methods. It showed that the faulty frequencies obtained by vibration analysis, acoustic analysis, power spectrum analysis and MATLAB programming were similar as applied on rolling element bearings

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