Bearing Health Analysis using Time - Frequency Plot and Statistical Analysis

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Abstract— Rolling element bearings are one of the most widely used elements in machines and their failure one of the most frequent reasons for machine breakdown. However any bearing defect (e.g. cracks, notch) occurring deteriorate the performance of the machine. Detection of the defect at its incipient stage and alerting/maintaining the user before it converts into a catastrophic failure is the aims of vibration monitoring technique. The vibration signals generated by faults in them have been widely studied and very powerful diagnostic techniques for observing bearing under a high rpm operating conditions. In the present research work vibration analyses have been focused to detect bearing fault at the early stage. To accomplish above tasks a bearing test rig, consisting of shaft-bearing in conjunction to a gear box and brake drum is used to demonstrate the effectiveness of vibration analysis real time data related to bearing vibrations. Afterwards a bearing with a crack is also examined for the fault detection. A faulty bearing vibration signal is acquired from the test rig; thereafter the fast Fourier transform is plotted to show the critical frequencies, bearing characteristics frequency and its harmonics for the online condition monitoring of the system. Post processing analysis is done for the time domain signal using the statistical parameters and scalogram showing the energy levels of impulses present in the signal is plotted as result. Both healthy & faulty signal are analyzed using wavelet transform to identify the fault in the bearing.

Key words: vibration analysis, critical frequencies, condition monitoring, wavelet transform, bearing fault

I. INTRODUCTION

The timely detection of faults or uneven working conditions, which may influence the performance, is expected to help in both reducing maintenance costs and increasing the machine efficiency. Bearing can be the largest cause of unscheduled reciprocating machines shutdowns. Hence to detect faults in Bearing Condition monitoring has been used by Time - Frequency plot and Vibration Analysis.

Condition monitoring is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of a developing failure. It is a major component of predictive maintenance. Vibration analysis is used to detect the early precursors to machine failure, allowing machinery to be repaired or replaced before an expensive failure occurs. All rotating equipment vibrates to some degree, but as older bearings and components reach the end of their product life, they begin to vibrate more dramatically and in distinct ways. Ongoing monitoring of equipment allows these signs of wear and damage to be identified well before the damage becomes an expensive problem.

The portable and permanently-mounted vibration analyzers are used in this monitoring process. The vibration analyzers record machine vibrations using sensors such as accelerometers and tachometers. Accelerometers are the ears of our instruments and are connected to rotating machinery such as electro-mechanical drives and gearboxes. The vibrations and movements of the equipment are then recorded. These recordings are later transferred to a computer and analyzed using the Lab View software, which provides a visual display of the vibration waveforms. We can compare these recordings over time and use the gradual development of new vibrations to detect wear at the earliest stages. This process is generically known as condition monitoring. When used correctly, it can result in huge cost savings compared to traditional maintenance methods.

A. Bearing

A bearing is a machine element that constrains relative motion and reduces friction between moving parts to only the desired motion. The design of the bearing may, for example, provide for free linear movement of the moving part or for free rotation around a fixed axis; or, it may prevent a motion by controlling the vectors of normal forces that bear on the moving parts.

1) *A Type of Bearings:-*
  - Rolling-element bearing
  - Ball Bearings
  - Cylindrical Bearings

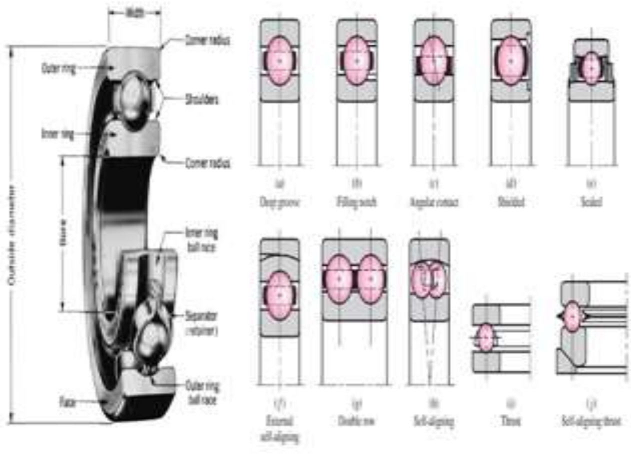


Fig. 1: Ball bearing & its types

B. Bearing Faults

Bearing faults usually start as small pits or spalls, and give sharp impulses in the early stages covering a very wide frequency range (even in the ultrasonic frequency range to 100 kHz). However, for some faults such as brinelling, where a race is indented by the rolling elements giving a permanent plastic deformation, the entry and exit events are not so sharp, and the range of frequencies excited not so wide.

1) A Types of Bearing Faults

- Ball Damage
- Inner & Outer Race defects
- Cage Defects

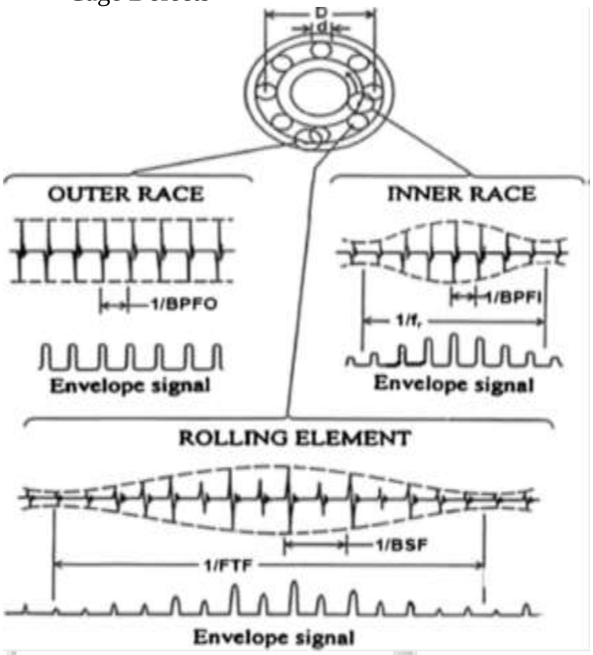


Fig. 2(A): Bearing Fault

2) B The Primary Causes Of Bearing Failures Are

1) Contamination, including moisture (Some sources claim that 40 percent of bearing failures are caused by contamination).
2) Overstress
3) Lack of lubrication
4) Defects created after manufacturing
5) Uneven dynamic forces in assembly due to multi-planer balancing
6) Misalignment
7) Debris/carbon/dust or dirt particles in oil during lubrication
8) Excessive wear
9) Friction & Excessive vibration

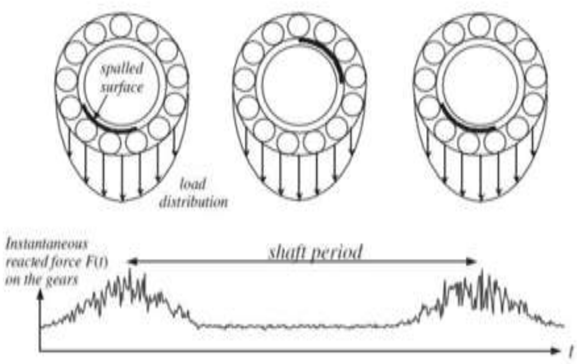


Fig. 2(B): Bearing Fault

II. METHODOLOGY

The fault diagnosis via condition monitoring of a bearing using the Time - Frequency plot vibration signal processing techniques & statistical analysis using ANSYS is the aim of the present work.

A. Time-Frequency Plot Method

The online vibration data were recorded for set of bearing and bearing with crack (fault), at a various speed and loading conditions using test rig. A spectral analysis is carried out in order to demonstrate and examine the presence of sidebands activity around the characteristics frequency resulting from the localized crack.

1) Development of bearing experimental test rig for the vibration analysis and to acquire the time domain signal respectively.
2) Mounted healthy bearing & faulty bearing on the experimental setup for vibration analysis.
3) Conduct the vibration analysis at different speed and different load for the bearing faults Acquisition of data/ pulse signal from the accelerometer via charge amplifier.
4) Note the frequency domain signal using the Lab view software for the amplitude v/s frequency and evaluated the maximum vibrating frequency (time domain signal) and its harmonics with respect to acceleration.
5) Result interpretation in terms of graphs between frequency and amplitude, acceleration and time and amplitude and time.
6) Calculation of statistical parameters using the Matlab.

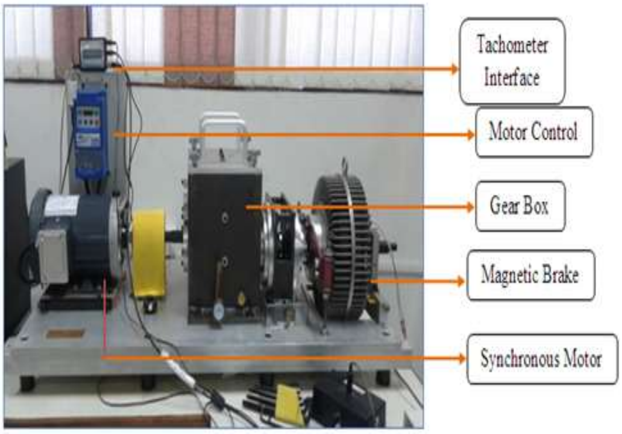


Fig. 3: Bearing Dynamics Simulator

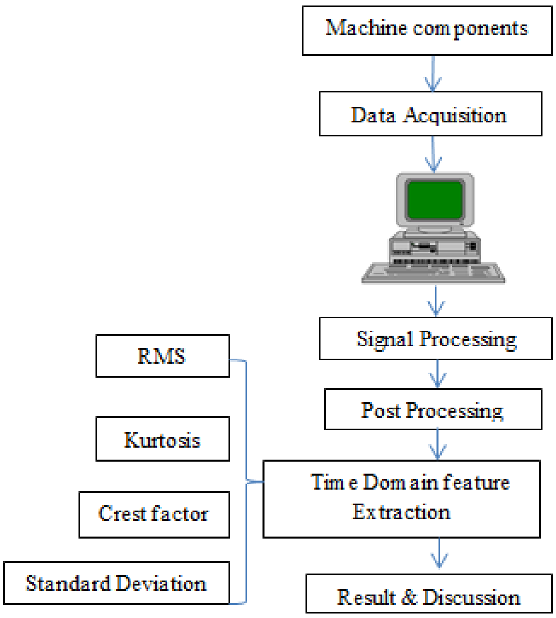


Fig. 4: Scheme of machinery fault diagnosis

B. Structural Analysis Using ANSYS (Simulation)

The steps involved in structural analysis of the bearing using ANSYS are as follows

1) Design and development of complete assembly of gearbox including bearing in CATIA
2) Importing the model in ANSYS Workbench module for static analysis of bearing under various load and boundary conditions
3) Assigning the element type and material properties of the bearing to simulate the real time environment on the bearing.
4) Development of meshed model for the with the element characterization so that the load can be easily applied to bearing and then it can be solved for complete set of equations
5) Solving the model for all the boundary conditions and nodal solutions are evaluated.
6) In the similar fashion modal analysis is performed for the mode shapes and the natural frequencies are calculated.

Fig. 5: Modeled ball bearing

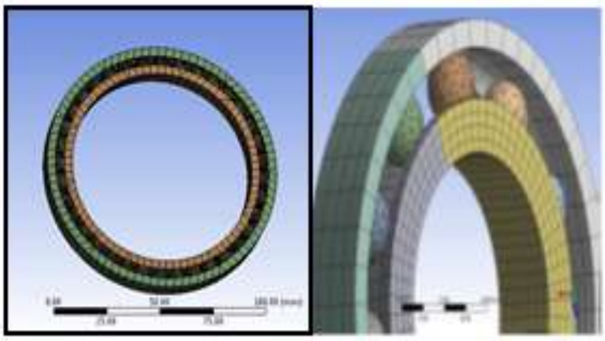
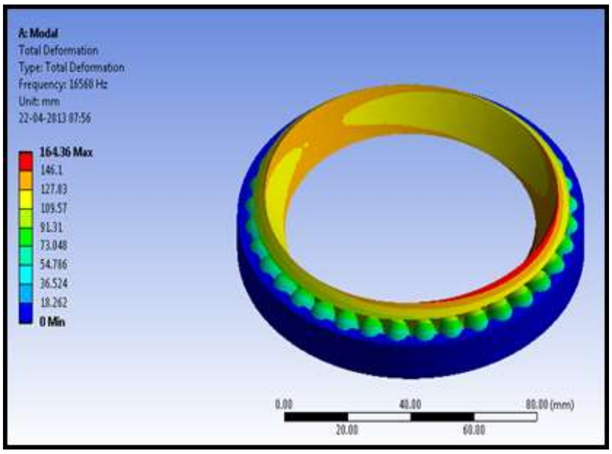


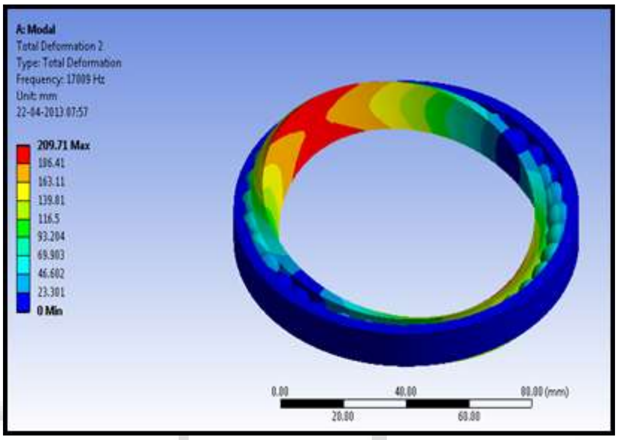
Fig. 6: Meshed model of bearing

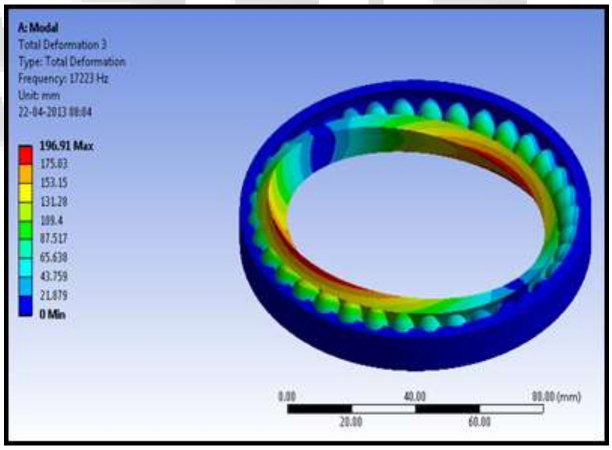
C. Computational Dynamics Analysis

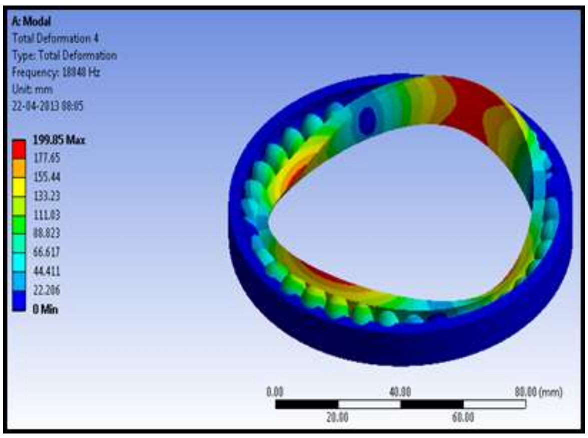
1) Without Defect

Here we have carried out the dynamic analysis for the natural frequency of the roller bearing using the block lanczos method in ANSYS platform. The mode shapes and respective values of deformation of bearing without defect are represented in the below mentioned Figure 7 and value of the natural frequency of respective mode shapes and max displacement of roller bearing without defect have been tabulated as table 1 as follow









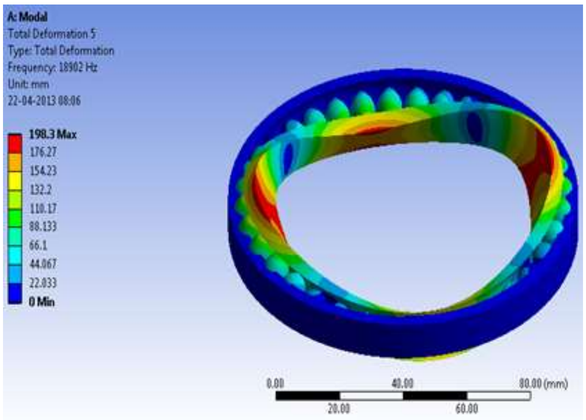


Fig. 7: Mode shapes of bearing without fault

Mode	Frequency (Hz)	Displacement (mm) (max)
1	16560	164.36
2	17009	209.71
3	17223	196.91
4	18848	199.85
5	18902	198.03

Table 1: Results for bearing without defect

In above pictures red areas shows that stress developed during loading are much higher than the limiting stress of material, whereas yellow area shows stress is in moderate limit and green area shows that stress are within the limits of ultimate stress of material of construction.

2) With Defect (notch)- In the bearing the notch are come in the inner ring of the bearing due to continuously long running operations are shown in Figure 8. The mode shapes and respective values of deformation of bearing with defect(notch) are represented in the below mentioned
3) Figure and value of the natural frequency of respective mode shapes and max displacement of roller bearing with defect(notch) have been tabulated as table 3 as follows:

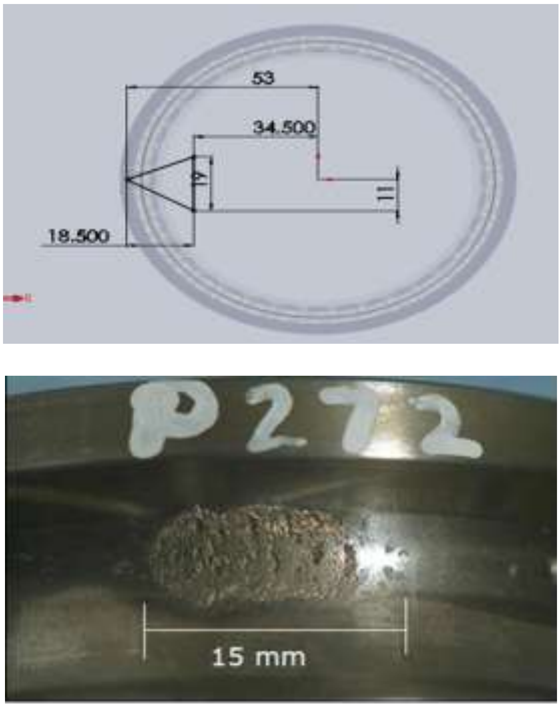
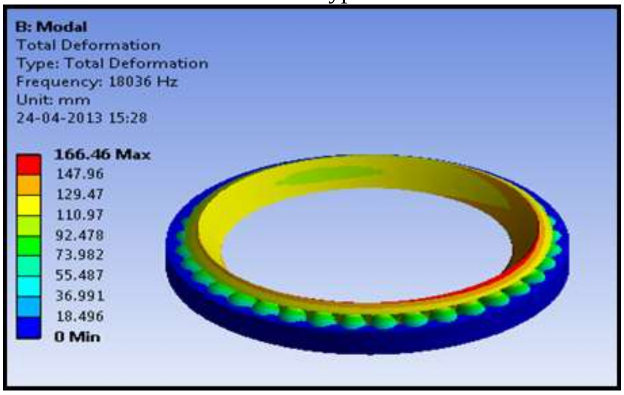
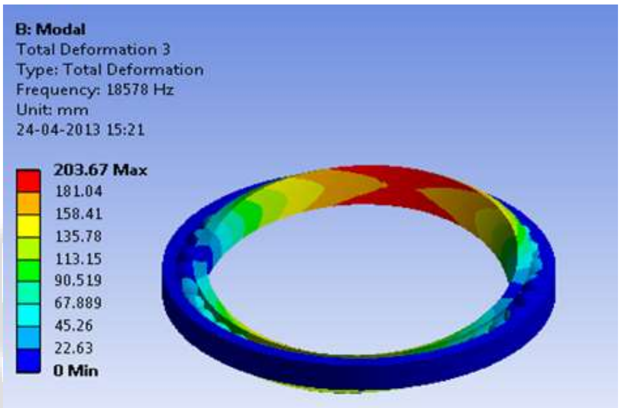


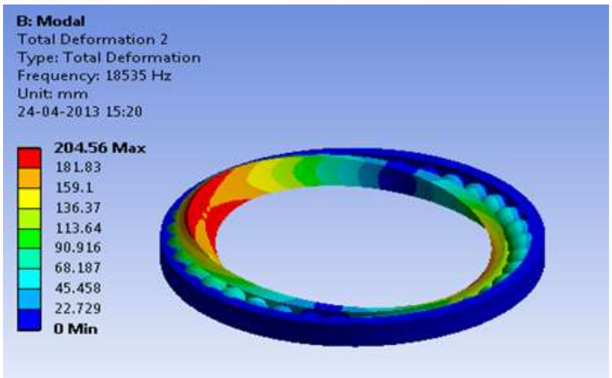
Fig. 8: Details of fault of bearing

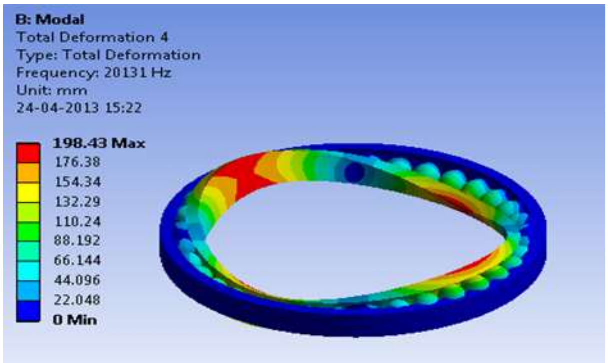
SET OF BEARINGS	Outer Race Defect	Inner Race Defect	Rolling Element Defect
SET 1 (mm)	0.35	0.41	0.29
SET 2 (mm)	0.39	0.47	0.35
SET 3 (mm)	0.44	0.56	0.38

Table 2: Fault type and size









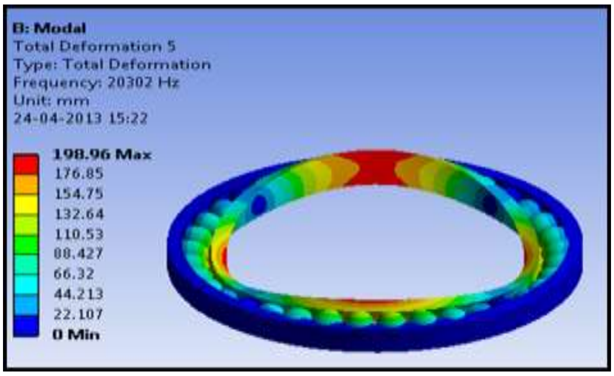


Fig. 9: Mode shapes of bearing with fault

Mode	Frequency (Hz)	Displacement (mm) (max)
1	18036	166.46
2	18535	204.56
3	18578	203.67
4	20131	198.43
5	20302	198.96

Table 3: Results for bearing with defect

III. FORMULAE/EQUATIONS

In order to calculate the different frequencies following formula/Equations are used:

A. *Ball-Pass Frequency, Outer-Race*

$$BPFO = \frac{nf_r}{2}\left\{1 - \frac{d}{D}\cos\emptyset\right\}$$

B. *Ball Pass Frequency, Inner Race*

$$BPFI = \frac{nf_r}{2}\left\{1 + \frac{d}{D}\cos\emptyset\right\}$$

C. *Fundamental Train Frequency (Cage Speed)*

$$FTF = \frac{f_r}{2}\left\{1 - \frac{d}{D}\cos\emptyset\right\}$$

D. *Ball (Roller) Spin Frequency*

$$BSF(RSF) = \frac{D}{2d}\left\{1 - \left(\frac{d}{D}\cos\emptyset\right)^2\right\}$$

Where, f_r is the shaft speed, n is the number of rolling elements and $\emptyset$ is the angle of the load from the radial plane. Note that the ball spin frequency (BSF) is the frequency with which the fault strikes the same race (inner or outer), so those in generals there are two shocks per basic period. Thus, the even harmonics of BSF are often dominant, in particular in envelope spectra.

The traditional techniques for the vibration based fault detection are typically based on the statistical measurement of the energy of vibration signal. The following statistical parameters can be used for the diagnosis purposes:

E. *Root Mean Squared*

It is defined as the square root of the average of the sum of the squares of the sum of the signal samples and is given by

$$RMS = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N}(x_i)^2\right]}$$

Where, x is the original time domain signal, N is the number of the samples and i is the sample index. RMS is used to identify the noise level in the signal.

F. *Crest Factor*

It is the ratio of the maximum positive peak to the RMS of the signal x, given by

$$CF = \frac{x_{0-pk}}{RMS}$$

Where, pk is the sample index for the maximum positive peak of the signal and x_{0-pk} is the value of x at pk: CF is used to find the increase in the presence of a small number of high-amplitude peaks, such as those caused by some types of local tooth damage.

G. *Kurtosis*

It is the fourth normalized moment of the signal and presents a measure of peakedness in the signal, i.e., the number and amplitude of peaks present in the signal. It is given by

$$kurtosis = \frac{N\sum_{i=1}^{N}(x_i - \bar{x})^4}{\left[\sum_{i=1}^{N}(x_i - \bar{x})^2\right]^2}$$

H. *Standard Deviation*

It represents the deviation from the average value and is given by

$$S_N{}^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2$$

The evaluation of the statistical parameters gives an idea of the fault initiation in the bearing after acquiring the time domain signal.

IV. RESULTS AND DISCUSSION

In order to illustrate the effectiveness of the proposed method, a simulation study followed by experimental investigation is conducted here for bearing test rig. Later the signals are acquired and then processed using time frequency analysis to know the fault appearing in the bearing. ANSYS simulation has been used for the simulation process for which cad model has been developed using the CATIA application. Later the frequency graphs of bearings have been developed in the ANSYS.

The results from the Harmonic Response (in a frequency range of 0 – 800Hz) to the Modal analysis of the CAD Model in ANSYS generated the following graphs related to acceleration and directional deformation:

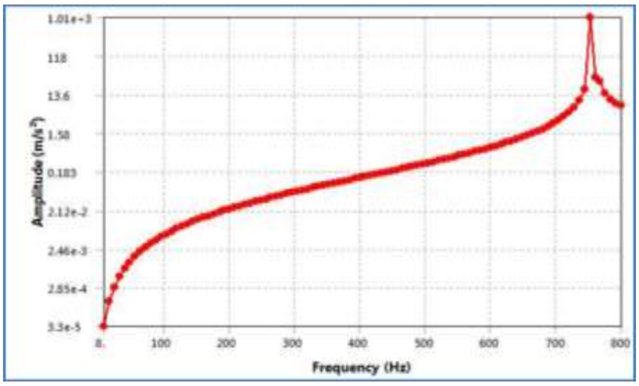


Fig. 10: ANSYS Acceleration Response (along X axis) in Frequency Domain

Later for the experimental analysis the values processed from the recordings are tableted and then the statistical indicators like, RMS, Standard deviation and kurtosis have been applied. The signals acquired for the different loads, so to know the fault appearing phenomenon plots of Kurtosis with respect to load has been developed here and placed in the later pages of thesis. The plots are taken at different speeds viz 10Hz, 20Hz and 50Hz.

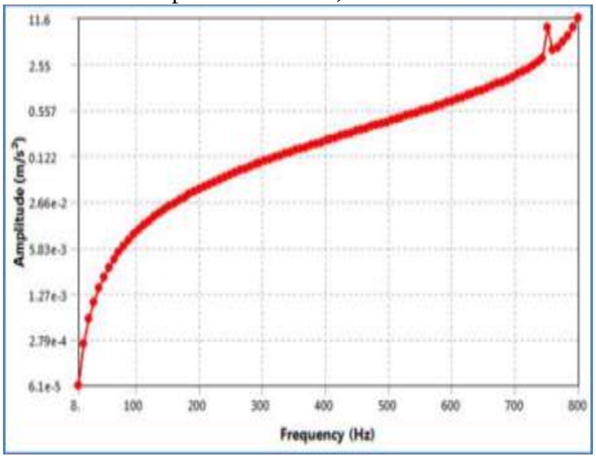


Fig. 11: ANSYS Acceleration Response (along Y axis) in Frequency Domain

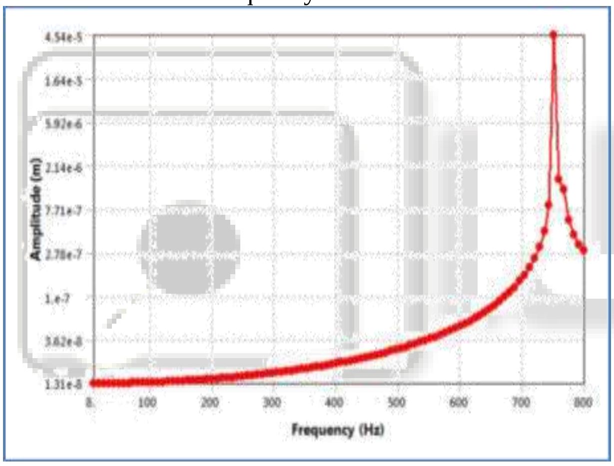


Fig. 12: ANSYS Deformation Response (along X axis) in Frequency Domain

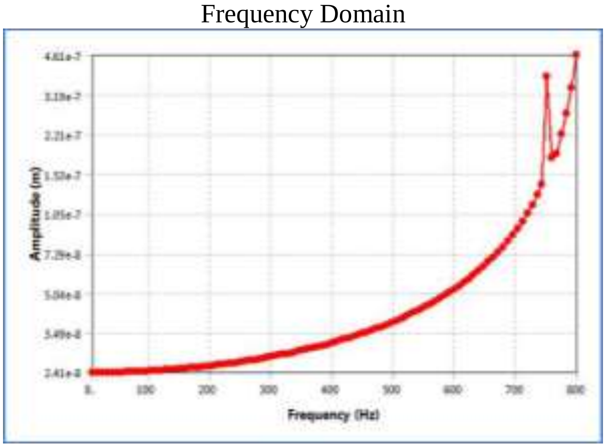


Fig. 13: ANSYS Deformation Response (along Y axis) in Frequency Domain

Load	RMS	Kurtosis	Crest Factor	Standard deviation
0%	2.73E-05	2.9222	4.0119	2.35E-05
30%	2.80E-05	2.9003	4.38	2.52E-05
60%	3.07E-05	2.9247	3.9159	2.66E-05
90%	3.54E-05	2.9329	4.0853	2.68E-05

Table 4: Statistical evaluation of the signal for healthy bearing at 10 Hz

Load	RMS	Kurtosis	Crest Factor	Standard deviation
0%	2.92E-05	3.0472	4.2183	2.66E-05
30%	3.07E-05	2.9338	4.1403	2.93E-05
30%	3.43E-05	3.0382	3.997	2.87E-05
90%	2.73E-05	3.0873	4.2183	2.73E-05

Table 5: Statistical evaluation of the signal for faulty bearing at 10 Hz

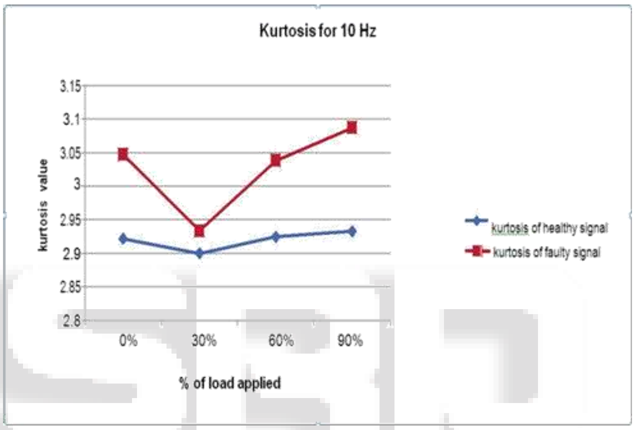


Fig. 14: Kurtosis comparison for different signals at 10Hz

Finally, a kurtosis plot is made for the evaluation of both the signals and it is found that, for fault the kurtosis value is increasing then that of the healthy bearing.

load	RMS	Kurtosis	Crest Factor	Standard deviation
0%	2.93E-05	2.9422	4.5703	2.72E-05
30%	3.14E-05	2.9419	3.9028	2.75E-05
60%	2.81E-05	2.9673	4.5235	2.79E-05
90%	3.20E-05	2.9471	4.1255	2.99E-05

Table 6: Statistical evaluation of the signal for healthy bearing at 20 Hz

load	RMS	Kurtosis	Crest Factor	Standard deviation
0%	2.97E-05	2.9905	4.1558	2.90E-05
30%	2.97E-05	3.1351	4.7566	2.81E-05
60%	3.65E-05	3.0929	3.7356	2.84E-05
90%	3.12E-05	3.0724	4.3561	2.92E-05

Table 7: Statistical evaluation of the signal for faulty bearing at 20 Hz

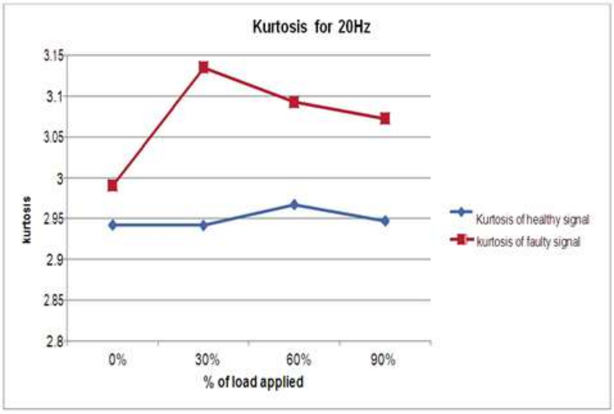


Fig. 15: Kurtosis comparison for different signals at 20Hz

Summing up the case of the faulty & healthy bearing for the 20Hz, it is found the Kurtosis vales are leading for the fault as shown in figure 10. Kurtosis for a standard normal distribution is three, which reflects for good conditions.

load	RMS	Kurtosis	Crest Factor	Standard deviation
0%	2.86E-05	2.9448	4.4068	2.85E-05
30%	3.18E-05	2.9098	3.9789	2.86E-05
60%	3.26E-05	2.9235	4.1728	3.19E-05
90%	2.97E-05	2.9637	4.0494	2.96E-05

Table 8: Statistical evaluation of the signal for healthy bearing at 50 Hz

load	RMS	Kurtosis	Crest Factor	Standard deviation
0%	2.93E-05	3.1754	4.6218	2.92E-05
30%	3.60E-05	3.5652	4.0905	2.93E-05
60%	3.52E-05	3.323	4.3695	3.56E-05
90%	3.96E-05	3.9502	4.9245	3.01E-05

Table 9: Statistical evaluation of the signal for faulty bearing at 50 Hz

Summing up the case of the faulty & healthy bearing for the 50Hz, it is found the Kurtosis vales are leading for the fault as shown in figure 11. Kurtosis for a standard normal distribution is three, which reflects for good conditions.

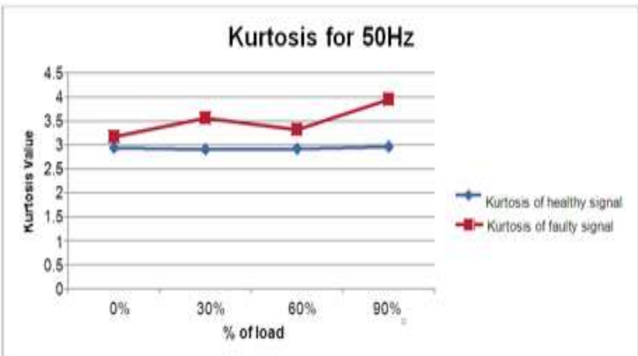


Fig. 16: Kurtosis comparison for different signals at 50Hz

A. Comparison between the Results of Vibration Analysis from Experimental Setup & ANSYS Simulation

After completing both experimental vibration analysis and ANSYS simulation we need to compare the results of both cases of bearing with defects and bearings without defects and will plot the graph that will show how much is deviation from real time results of vibration analysis and ANSYS simulation.

Below is chart which shows values of frequency for from experiments and ANSYS for bearing without faults and with faults respectively.

Characteristic frequency number	Without fault		With fault	
	From ANSYS	From Exp.	From ANSYS	From Exp.
1	16560	16448	18036	18097
2	17009	17024	18535	18415
3	17223	17105	18578	18590
4	18848	18801	20131	20191
5	18902	18922	20302	21001

Table 10: Results of vibration analysis from experimental setup & ANSYS simulation

From below plotted graphs it is very much clear that results of both experiments and ANSYS simulation it is very much clear that values of both frequencies are in close vicinity of each other, hence our experimental vibration analysis is verified.

B. Comparison of Frequency for Bearing without Fault

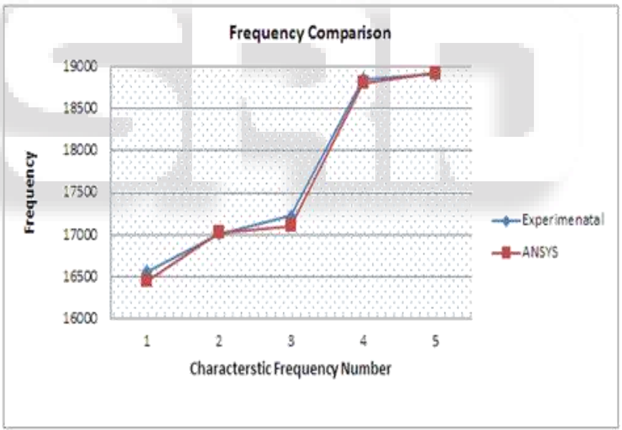


Fig. 17: Comparison of frequency for bearing without fault

C. Comparison of Frequency for Bearing with Fault

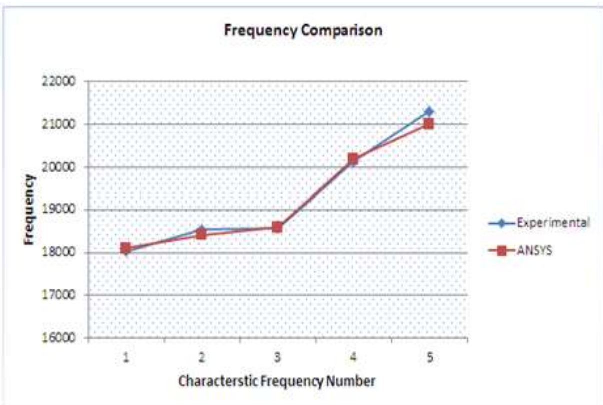


Fig. 18: Comparison of frequency for bearing with

V. CONCLUSION

Aim of the research is to develop a novel intelligent system to tackle with bearing faults. The strategy is to develop more robust techniques at each processing stage to improve the condition monitoring reliability. First, a new signal processing technique, the wavelet spectrum analysis, is proposed to extract the representative features that are related to the incipient bearing faults. A strategy is suggested for the deployment of wavelet center frequencies. To enhance the feature characteristics, a statistical parameters based calculation is performed to extract the feature related to the fault of the bearing.

Kurtosis specified the fault as we have found that the Kurtosis value for the healthy and the faulty bearing are different as for the faulty bearing the values of the kurtosis goes on increasing in every case whether for 10Hz, 20Hz and 50Hz. We kept the inputs constant and got healthy and faulty signals, there is change found in the amplitude of the critical frequency and in the side bands emerged for the high speeds. In order to verify the experimental results simulation analysis has been performed using ANSYS and results are founds within acceptable limits.

A. Cost Analysis of Experimental Setup of Bearing Dynamics Simulator (BDS)

Cost Analysis of Experimental setup of Bearing Dynamics Simulator(BDS)				
S. No.	Name of Component	Qty (Nos.)	Price (USD)	Total Price (USD)
1	1 HP AC Motor With Built-In Faulted Bearings (G-FBM-1)	1	2500	2500
2	Bearing Fault Kit (G-BFK-1)	4	75	300
3	Bearing without fault Kit (G-BFK-2)	4	85	340
4	Spur Gears	4	70	280
5	Shafts	2	55	110
6	Shaft encoder (G-ENC) Tachometer	1	60	60
7	Transducers	2	100	200
8	PC Motor Control Kit (G-PCMK)	1	150	150
9	PC Load Control Kit (G-PCLK)	1	250	250
10	Accelerometer	1	400	400
11	Magnetic Brake	1	570	570
		Total Price (USD)		5160
		Total Price (INR)		309600

Given above is detailed breakup of cost of bearing dynamics simulator manufactured by Spectra quest Inc., USA. This experimental setup can also be used for gear fault analysis as we can acquire the signal of vibration for gears also after mounting the faulty and healthy gear on experimental setup. Sources of purchase for experimental setup http://spectraquest.com/

B. Annual Maintenance Cost

Annual maintenance cost is very less for the setup as only we need to maintain only AC motor of setup in the case of burning of motor, apart from motor all the components of setup are having long life, and hence cost of maintenance is almost negligible.

VI. SCOPE OF FUTURE

In order to minimize bearing downtime and to avoid performance degradation, a practical and tough monitoring system like is needed to provide early warnings of malfunction or possible damage, which may lead to sudden or even devastating failures.

1) The proposed bearing fault detection techniques and decision-making schemes will be applied to other mechanical systems such as gearboxes and engines.
2) More investigation related to the diagnoses of advanced bearing faults and distributed bearing defects will be conducted.
3) Oil analysis responses earlier than vibration analysis in case of faults like wear, pitting because theses faults release the debris in oil and can be easily detected by wear debris analysis.
4) Moreover deterioration in oil quality and %RH increase also gives indication about the health of bearing.
5) Noise and acoustics analysis may also be used to monitor the condition of the machine elements like rotors, gears.
6) While other faults like crack, eccentricity, misalignment can be detected by vibration analysis on the early stage.
7) So, combining these techniques gives more reliable condition monitoring. A multi sensor data strengths of vibration analysis techniques and reduces the false alarm and increase the reliability.

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