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Condition Monitoring of Ball Bearings Using Statistical Analysis

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Abstract* − *The study investigated the variation of statistical parameters of vibration signals acquired from Ball bearings with respect to speed using an experimental set up. Accelerometers mounted on the bearing housing and connected to Sound and Vibration Analyzer (SVAN) 954 were used to measure the radial accelerations from the bearing housing. The RMS value & kurtosis analysis validates that the ball bearing health can be fairly monitored using frequency domain Analysis. The method proves to be a simple, quick & cost effective method in the condition monitoring of ball bearings & is most suitable for random signals such as from bearings.

Keywords− ***SVAN 954, RMS Value, Kurtosis analysis, Ball bearing health, Random signals***

Introduction

Maintenance cost is one of the major operating costs in manufacturing companies. It involves spare parts cost, breakdown cost and manpower cost. Unexpected breakdowns, replacement and repair expenses from catastrophic failures indulge in loss of output due to machinery downtime. Adoption of predictive and preventive maintenance procedures significantly reduces these losses. This is essential in maintenance management to enhance the product quality. Predictive maintenance requires continuous measurement of machine operating parameters such as temperature, power consumption, vibration, noise, forces.

A Condition Based Monitoring (CBM) program consists of three key steps as shown in Figure 1.

A) Data acquisition (Information collecting):

A data or signal relevant to system health is collected.

B) ***Data processing*** (Information handling):

A data or signal collected is analyzed for its better interpretation.

C) ***Maintenance*** (Decision making):

Here, efficient maintenance policies are recommended.

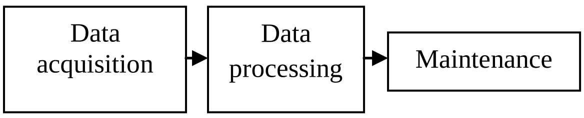

Figure 1: Steps in CBM

N. Tandon et al. [i] in 1997 proposed an analytical model for predicting the vibration frequencies of rolling bearings and the amplitudes of significant frequency components due to a localized defect on outer race or inner race or on one of the rolling elements under radial and axial loads. Arnaz S. Malhi [ii] in 2002 did a preliminary vibration analysis of a rolling element passing over a single point defect on the outer ring of a ball bearing using FEA software ANSYS. Author extracted vibration signals for two different defect sizes and proposed an index for comparison of different defect sizes. Sadettin Orhan et al. [iii] in 2005 presented vibration monitoring and analysis case studies and examined those in machineries that were running in real operating conditions using spectral analysis. Robert B. Randall et al.[iv] in 2010 presented a tutorial to guide the reader in the diagnostic analysis of acceleration signals from rolling element bearings in the presence of strong masking signals from other machine components such as gears. M.S.Patil et al. [v] in 2010 presented an analytical model for predicting the effect of a localized defect on the ball bearing vibrations. Authors also investigated the effect of the defect size and its location on the ball bearing vibrations. Sylvester A. Aye [vi] in 2011 investigated on the sensitivity of using a contact and a non contact method in condition monitoring of taper roller bearings.

II. Material and Methodology

An experimental set up developed is as shown in Figure 2. A shaft is supported by 2 test bearings at its ends which is driven by a variable Speed DC motor. A V-belt drive connects motor to the system to achieve higher speeds of rotation. SVAN 954 Vibration Analyzer is used to pick up the acceleration signals. The signals for healthy & faulty bearings were obtained for various speeds with different unbalance mass on the shaft.

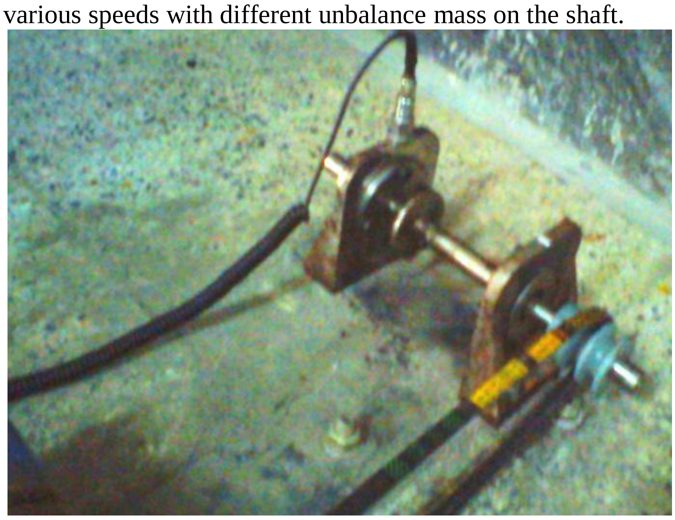

Figure 2: Experimental Set Up

The block diagram of instrumentation is as shown in Figure 3. It consists of an Acceleration Sensor, FFT Spectrum Analyzer, dimmerstat & a digital tachometer. Acceleration Sensor has a

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magnetic base for mounting on the bearing housing & the other end is connected to the FFT Spectrum Analyzer. FFT Spectrum Analyzer is used to record the corresponding vibration spectrum. Dimmerstat is used for varying the voltage supplied to DC motor to vary its speed. A digital tachometer is used to measure different shaft speeds.

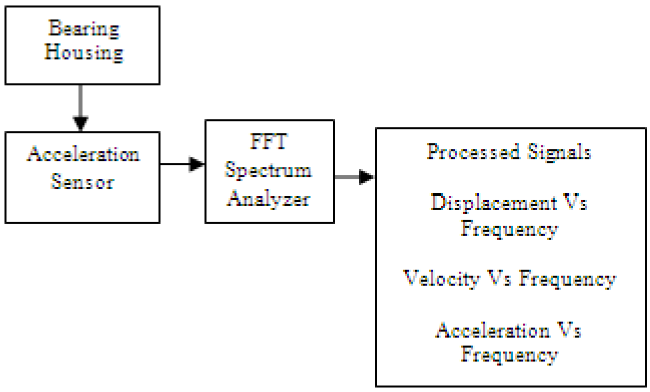

Figure 3: Instrumentation Used

The defect to the outer race of two test bearings was produced by Wire Cut EDM (Electro Discharge Machining). It consists of a through circular hole of 0.8 mm diameter to the outer race of a bearing as shown in Figure 4.

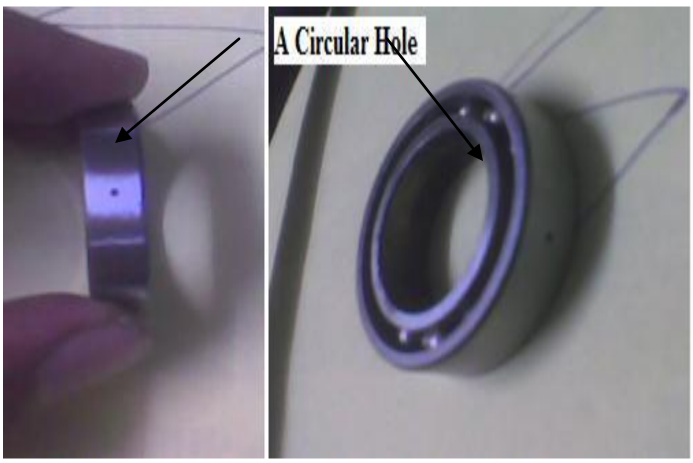

Figure 4: A Defect Introduced

When a rolling element cage rotates with a constant rotational frequency of ω_c, a parametrically excited vibration signal is generated & transmitted through outer race. Defect in the outer race, inner race & rolling element generate vibrations at distinct frequencies. Assuming no slip & outer race to be stationary, the general form of bearing defect frequency equations are given below [v].

Rolling element passage frequency of outer race (Defect frequency of outer race)

$$\text{Cage frequency} = \omega_c = \frac{\omega i\left(1-\frac{dh\cos(\alpha)}{dm}\right)}{2}\ \text{Hz} \quad (1)$$

Rolling element passage frequency of inner race (Defect frequency of inner race)

$$\omega_{ep} = \frac{z\omega i\left(\frac{1-dh\cos(\alpha)}{dm}\right)}{2} \quad \text{Hz} \quad (2)$$

Ball passage frequency (Ball Spin frequency)

$$\omega_{ip} = \frac{z\omega i\left(\frac{1+dh\cos(\alpha)}{dm}\right)}{2} \quad \text{Hz} \quad (3)$$

Theoretical calculation of the above listed frequencies at different Speeds (RPM) is shown in Table I.

$$\omega_{rp} = \frac{\omega i\ dm\left\{1-\left(\frac{dh\cos(\alpha)}{dm}\right)2\right\}}{2dh} \quad \text{Hz} \quad (4)$$

Table I : Theoretical Calculation of the Frequencies at Different Speeds

RPM	Rotational frequency (Hz)			Defect frequency (Hz)		
	ω_i	ω_e	ω_c	ω_{ip}	ω_{ep}	ω_{rp}
2298	38.3	0	14.7	306.4	191.5	78.5
1054	17.5	0	6.75	140.4	87.8	36.0
1474	24.5	0	9.44	196.4	122.8	50.3
1000	16.6	0	6.4	133.2	83.3	34.1
1078	17.9	0	6.9	143.6	89.8	36.8
1724	28.7	0	11.0	229.8	143.6	58.9

III Results and Tables

A. Procedure

1. Experimental readings were taken for different shaft Speeds and different unbalances on the shaft, for LHS (Left Hand Side) & RHS (Right Hand Side) bearings respectively. As the defect was introduced only in the LHS Bearing, we discuss the same further. An unbalance in the form of mass of bolt was added on the circular disc. The six cases considered for obtaining results were healthy bearing with no bolt, healthy bearing with one bolt, healthy bearing with two bolts, and defective bearing with no bolt, defective bearing with one bolt, and defective bearing with two bolts.
2. An Acceleration sensor with its magnetic probe was attached to test bearing housing. A FFT Spectrum Analyzer was powered by external DC Source & connected to the sensor.
3. A DC Motor was started. The shaft speed was measured using Digital Tachometer. At the known RPM of a shaft, the spectrum was recorded through FFT Spectrum Analyzer.
4. The Speed of motor was gradually increased using dimmerstat which was connected in series with motor. The corresponding spectra were recorded through FFT Spectrum Analyzer.
5. For introducing unbalance, a mass equal to mass of one bolt was added on the circular disc. The Steps 3 & 4 were now repeated.

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6. For increasing unbalance, another bolt was added on the circumferential hole of a circular disc. The Steps 3 & 4 were repeated further.
7. The test bearing was then dismantled from the housing. A known defect was introduced in the same & further it was reassembled.
8. The steps 3,4,5,6 were repeated for the defective Bearing.
Thus the six cases were experimentally tested.

B. Observed Spectra

For each case, the spectrum was recorded for 10 different shaft Speeds. The observed acceleration spectra for each of the six cases are as shown in the following Figures.

Case I: Healthy Bearing with No Bolt (Speed= 2298 rpm)

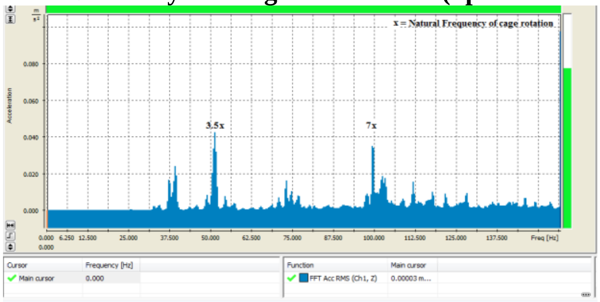


Figure 5: Acceleration Spectrum for Case I at 2298 rpm

Case II: Healthy Bearing with One Bolt (Speed= 1054 rpm)

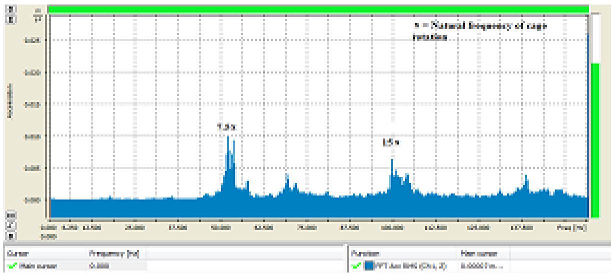
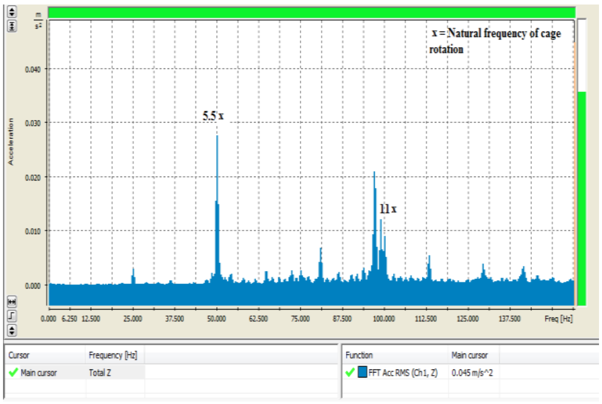


Figure 6: Acceleration Spectrum for Case II at 1054 rpm

Case III: Healthy bearing with Two Bolts (Speed= 1474 rpm)



Case IV: Defective bearing with No Bolt (Speed = 1000 rpm)

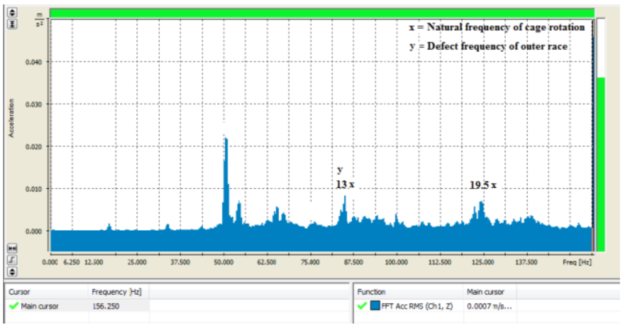
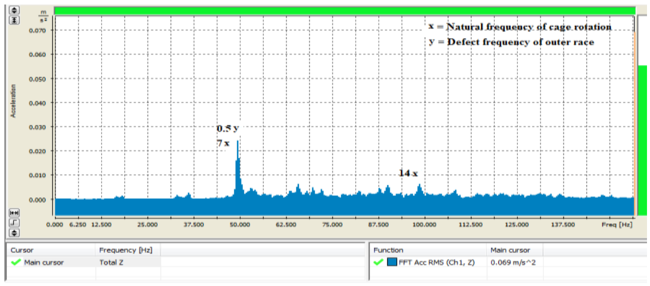


Figure 7: Acceleration Spectrum for Case III at 1474 rpm and for Case IV at 1000 rpm

Case V: Defective Bearing with One Bolt (Speed = 1078 rpm)



Case VI: Defective Bearing with Two Bolts (Speed = 1724 rpm)

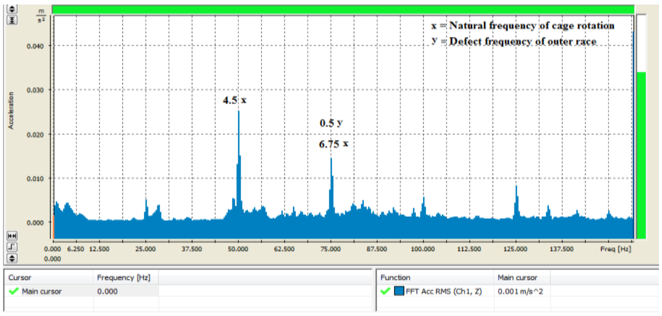


Figure 8: Acceleration Spectrum for Case V at 1078 rpm and for Case VI at 1724 rpm

C. Inference from the Experimental Results

1. For healthy bearings, the peak amplitudes of acceleration (m/s^2) were observed at whole & half multiples of natural frequency of cage rotation. (3.5 ω_c, 7 ω_c etc.)

2. For defective bearings, the peak amplitudes of acceleration (m/s^2) were observed at-

a) Whole & half multiples of natural frequency of cage rotation.(13 ω_c, 19.5 ω_c etc.)

b) Whole & half multiples of defect frequency of outer race (ω_{ep}, 0.5 ω_{ep}).

D. RMS Value

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For a dispersed data having N number of data points & X_m as an arithmetic mean, a root mean square value is defined as square root of sum of squares of all deviation values divided by Number of samples, where Xi is i^{th} data point.

$$RMS = \sqrt{\frac{\sum_{i=1}^{N}(Xi-Xm)^2}{N}} \quad (5)$$

E. Kurtosis For a dispersed data having N number of data points & X_m as arithmetic mean, a Kurtosis is a measure of peakedness of the probability distribution of a real valued random variable. Kurtosis is a measure of whether the data are peaked or flat relative to a normal distribution. The kurtosis is calculated by following formula-

$$Kurtosis = \frac{\sqrt{\frac{\sum_{i=1}^{N}(Xi-Xm)^2}{N}}}{RMS^4} \quad (6)$$

Where X_i = i^{th} Data Point,

RMS = Root Mean Square Value

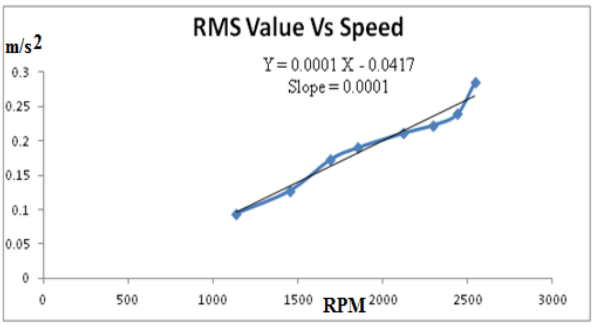
F. RMS Value & Kurtosis Analysis

The data points & variation of RMS and Kurtosis values of Acceleration with Speed for the Case I are given in Table II & Figure 9 respectively.

Case I : Healthy Bearing with No Bolt

Table II : Data points for RMS and Kurtosis values of Acceleration with Speed

Speed(RPM)	RMS Value (m/s^2)	Kurtosis
1136	0.0944	6.73
1454	0.128	50.8
1692	0.173	24.4
1852	0.19	29.53
2118	0.211	26.83
2298	0.223	21.25
2440	0.239	36.57
2544	0.285	120.68



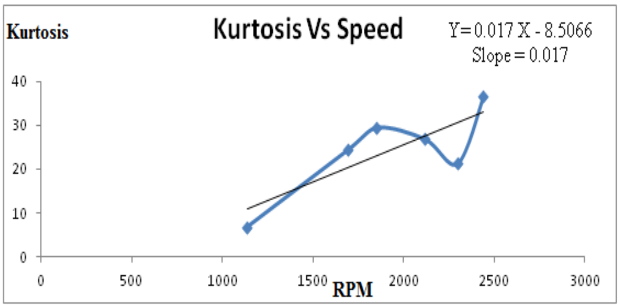


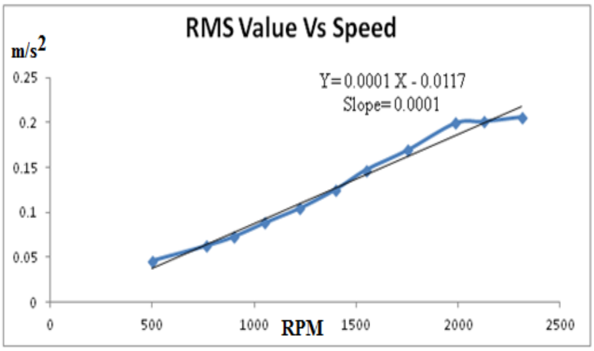
Figure 9: Variation of RMS and Kurtosis values with Speed & their "Best Fit" for Case I

The data points & variation of RMS & kurtosis values of Acceleration with Speed for the Case II are given in Table III & Figure 10 respectively.

Case II: Healthy Bearing with One Bolt

Table III : Data points for RMS & Kurtosis values of Acceleration with Speed

Speed (RPM)	RMS Value (m/s^2)	Kurtosis
500	0.0457	3.815
765	0.06237	5.081
900	0.07244	11.37
1054	0.0881	16.21
1222	0.104	14.89
1400	0.125	16.72
1550	0.147	35.77
1754	0.169	35.15
1988	0.199	35.76
2126	0.201	40.58
2314	0.206	54.51



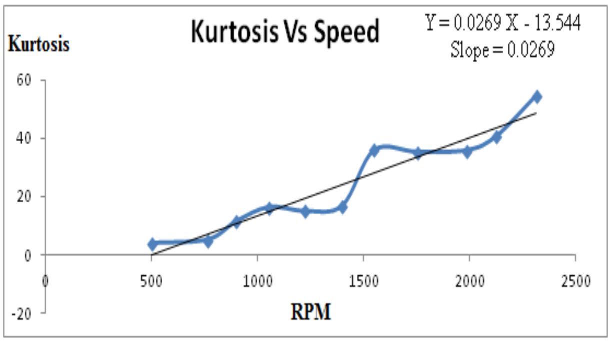


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Figure 10: Variation of RMS and Kurtosis values with Speed & their "Best Fit" for Case II

The data points & variation of RMS & Kurtosis values of Acceleration with Speed for the Case III are given in Table IV & Figure 11 respectively.

Case III: Healthy Bearing with Two Bolts

Table IV: Data points for RMS and Kurtosis values of Acceleration with Speed

Speed (RPM)	RMS (m/s^2)	Kurtosis
756	0.081	152.9815
1040	0.12	121.2058
1278	0.153	18.06846
1474	0.197	51.83483
1762	0.248	29.45817
2154	0.272	26.37381
2290	0.309	119.7005
2340	0.346	43.16412
2442	0.342	43.16412

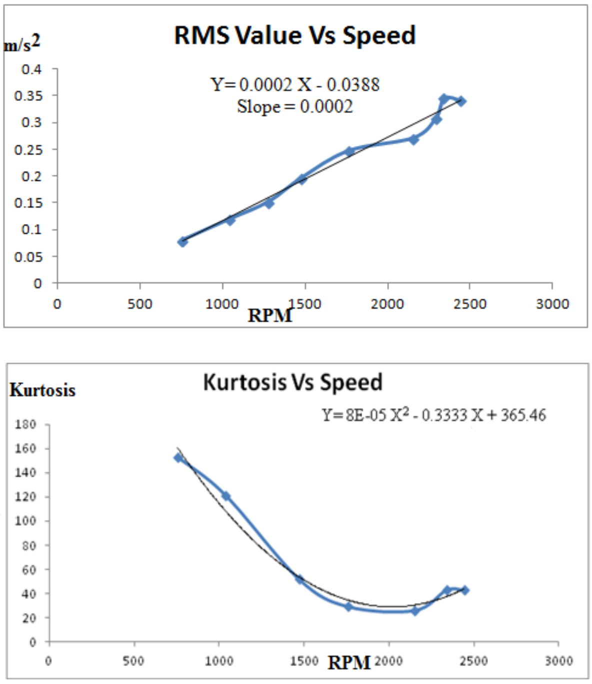


Figure 11: Variation of RMS and Kurtosis values with Speed & their "Best Fit" for Case III

The data points & variation of RMS & Kurtosis values of Acceleration with Speed for the Case IV are given in Table V & Figure 12 respectively.

Case IV: Defective Bearing with No Bolt

Table V: Data points for RMS & Kurtosis values of Acceleration with Speed

Speed (RPM)	RMS Value (m/s^2)	Kurtosis
595	0.479	3.0133
885	0.75	16.288
1000	1.274	40.115
1162	0.923	10.639
1318	1.023	58.395
1512	1.23	125.78
1638	1.38	9.7145
1818	1.603	11.369
2300	2.541	13.573
2666	3.126	16.023

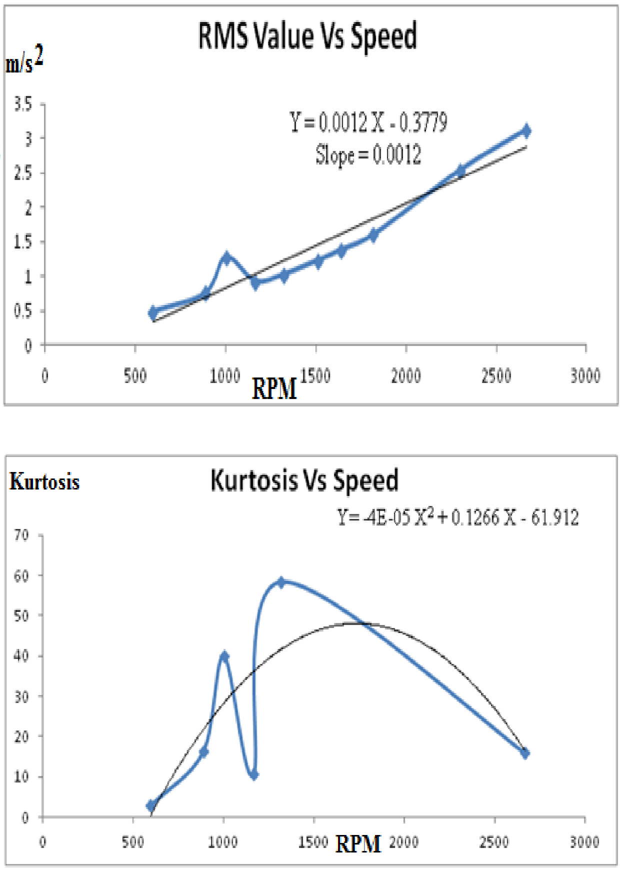


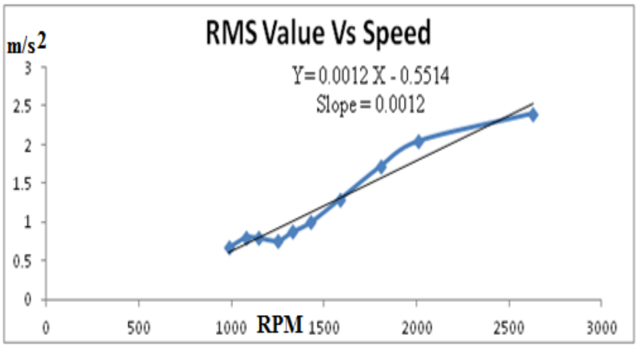
Figure 12: Variation of RMS and Kurtosis values with Speed & their "Best Fit" for Case IV

The data points & variation of RMS & kurtosis values of Acceleration with Speed for the Case V are given in Table VI & Figure 13 respectively.

Case V: Defective Bearing with One Bolt

Table VI: Data points for RMS and Kurtosis values of Acceleration with Speed

Speed (RPM)	RMS Value (m/s^2)	Kurtosis
986	0.676	19.9489
1078	0.804	59.1757
1146	0.804	173.477
1252	0.767	7.23465
1332	0.881	20.8541
1428	1.000	5.05221
1589	1.303	60.2190
1804	1.718	12.2214
2008	2.042	27.5438
2630	2.398	36.5781



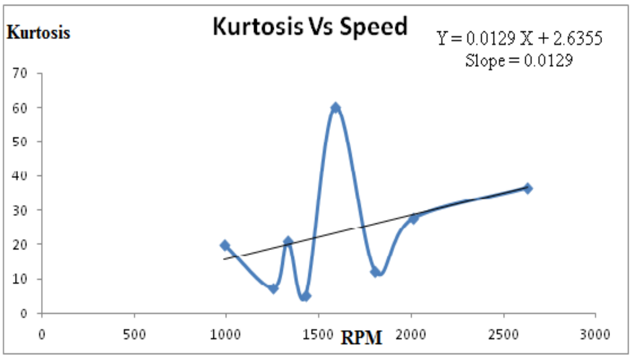


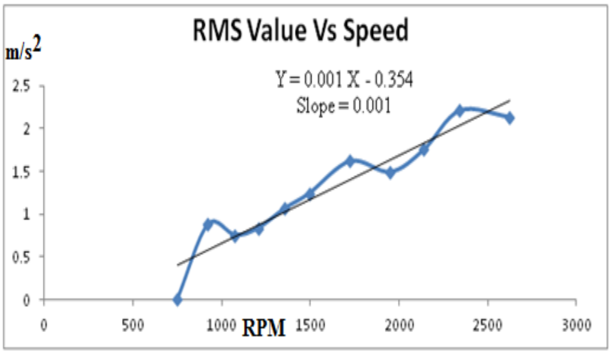
Figure 13: Variation of RMS and Kurtosis values with Speed & their "Best Fit" for Case V

The data points & variation of RMS & Kurtosis values of Acceleration with Speed for the Case VI are given in Table VII & Figure 14 respectively.

Case VI: Defective Bearing with Two Bolts

Table VII: Data points for RMS and Kurtosis values of Acceleration with Speed

Speed (RPM)	RMS Value (m/s^2)	Kurtosis
750	0.017	8.00
920	0.881	173.05
1074	0.759	10.10
1204	0.841	4.11
1356	1.072	10.57
1492	1.245	20.71
1724	1.622	55.11
1950	1.496	43.34
2140	1.758	23.09
2342	2.213	17.06
2624	2.138	20.01



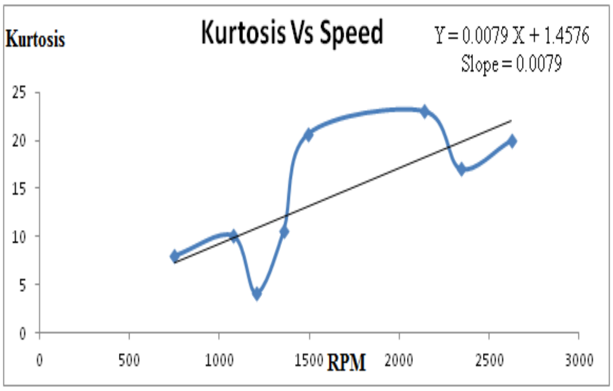


Figure 14: Variation of RMS and Kurtosis values with Speed & their "Best Fit" for Case VI

G. Inference from RMS Value & Kurtosis Analysis

Table VIII shows the Slopes of RMS Value Vs Speed "Best fit" curve for the six cases considered.

Table VIII: Slopes of RMS Value Vs Speed "Best fit" curve for the six cases

Case	Description	Slope of the RMS Value Vs Speed "Best fit"
I	Healthy Bearing With No Bolt	0.0001
II	Healthy Bearing With One Bolt	0.0001
III	Healthy Bearing With Two Bolts	0.0002
IV	Defective Bearing With No Bolt	0.0012
V	Defective Bearing With One Bolt	0.0012
VI	Defective Bearing With Two Bolts	0.001

1. For healthy bearings, slope of the RMS Value Vs Speed best fit curve gradually increases as unbalance increases.

2. As the defect is introduced in the bearing, the corresponding slope values shoot approximately to 10 times of their values for healthy bearings subjected to same unbalance.

Table IX shows the Slopes of Kurtosis Vs Speed "Best fit" curve for the six cases considered.

Table IX: Slopes of Kurtosis Vs Speed "Best fit" curve for the six cases

Case	Description	Slope of the Kurtosis Vs Speed "Best fit" curve
I	Healthy Bearing With No Bolt	0.017
II	Healthy Bearing With One Bolt	0.0269
III	Healthy Bearing With Two Bolts	-
IV	Defective Bearing With No Bolt	-
V	Defective Bearing With One Bolt	0.0129
VI	Defective Bearing With Two Bolts	0.0079

1. For healthy bearings, slope of the Kurtosis Vs Speed best fit curve decreases with unbalance. The trend is reverse of the trend of RMS Values with speed. This can be validated by the Equation (6).

$$\text{Kurtosis} = \frac{\sqrt{\frac{\sum_{i=1}^{N}(Xi-Xm)^2}{N}}}{RMS^4} \qquad (6)$$

2. For defective bearings, slope of the Kurtosis Vs Speed best fit curve decreases with unbalance.

3. Bearing signals are not periodic but stochastic (or random) having indeterminacy. This allows them to be separated from deterministic signals such as from gears [v]. Thus, the kurtosis curves reflect an uncertainty in their trend.

IV. Conclusions

The development of bearing condition monitoring test rig was successfully carried out which can be used to determine the health of a bearing used in the rotating machinery.

The RMS value analysis validates that the ball bearing health can be fairly monitored using frequency domain analysis. The Proposed Statistical analysis proves to be a simple, quick & cost effective method in the condition monitoring of ball bearings. The method proves to be most suitable for random signals such as from bearings.

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