International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 05 Issue: 05 | May-2018 www.irjet.net p-ISSN: 2395-0072

Effect of Amplitude at some bearing speeds and radial loads on Defective Deep Groove Ball Bearing

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Abstract - *Rolling element bearings are widely used as low friction joints between rotating machine components. In industrial applications, bearings are considered as critical mechanical components and a defect in such a bearing, unless detected in time, causes malfunction and may even lead to catastrophic failure of the machinery. The research work presented focuses upon the detection of a localized defect in a single row ball bearing using vibration analysis. For bearing analysis, frequency domain approach is taken followed by experimentation. Defected single row ball bearings are tested under different speed and loading conditions, and resulting vibration signals are then processed using vibration-based techniques in frequency domain. DOE method like Response Surface Method (RSM) is used as a medium for fault detection. After applying RSM, we can drawn conclusion in case of inner race fault, the magnitude of velocity amplitude increases with increasing the speed while the magnitude of velocity amplitude initially increases with increasing radial load then its magnitude decreases with increasing load. In case of outer race fault, the magnitude of velocity amplitude initially increases with increasing speed then its magnitude decreases with increasing speed while the magnitude of velocity amplitude decreases with increasing radial load.*

Key Words: **Deep groove ball bearing, Amplitude, Frequency domain approach, Response Surface Method, ANOVA**

1. INTRODUCTION

In most of industries, the rotating machines play a vital role in the most of the applications due to its large utilization. So it is necessary to maintain all the components of rotating machines in order to avoid sudden failure of machines or plants. Among all components of rotating machine, bearing is most important components because it causes approximate 30-50% of failure of the rotating machine. The failure of bearing is primary cause of failure of rotating machine. The bearing generally fails due to the fatigue stress failure. When the endurance strength of bearing materials exceed over the permissible limit then the fatigue cracks develop on the surface of bearing and these crack are gradually propagated and convert into large spalls or pits. These spalls are dangerous for catastrophic failure of rotating machine and also for operator who operates machine. So the fault diagnosis is important to avoid catastrophic failure and human injuries.

There are various methods present to detect the faults and monitor the condition of bearing. The analysis of vibration generally has done using frequency domain analysis. Vibration signal is measured from Fast Fourier Transform (FFT) signal processing techniques, are generally employed to extract the fault sensitive features to serves as the monitoring indices. Design of experiments (DOE) helps to understand how to influence factors related to the system. These methods such as factorial design, Response Surface Method (RSM) and so on.

1.1 FREQUENCY DOMAIN APPOROACH

Among the fundamental parts of the bearing, the inner race, outer race, ball and cage, which are put in the space between the rings and make turning feasible for them, are unequivocally machined. Be that as it may, because of the unseemly grease of the bearing rolling components, lacking bearing choice, despicable mounting, indirect failure, and material imperfections and manufacturing errors, different deformities can be happened in these parts. When all is said in done, the movement of the bearing fault is portrayed by 4 particular zones, as appeared in Fig. 1.1.

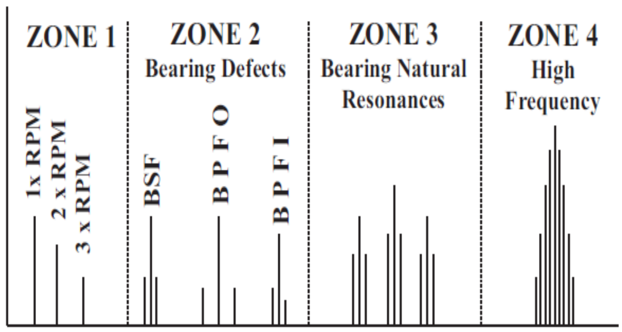

Fig-1. Frequency domain of the vibration signal during bearing failure.

Review the four zones of the frequency spectrum of the vibration signal, the level of the danger of catastrophic failure can be assessed bearing faults. A solid choice calculation can be founded on zone 2, zone 3 or zone 4 for quick interpretation and classification of the bearing faults.

$$f_c = \frac{f_r}{2}\left(1 - \frac{d}{Dm}\cos\alpha\right) = {f_{bi}}/{N_b} \quad \text{.............(1)}$$

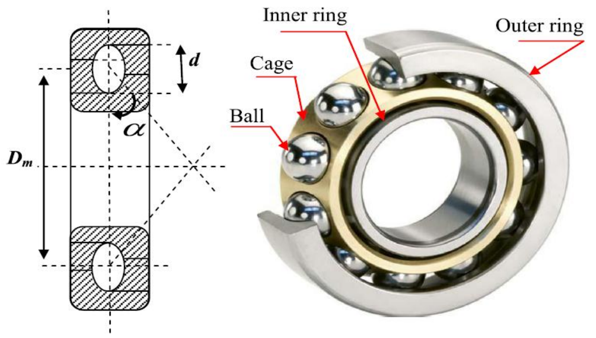

Fig-2. Structure of ball bearing

$$f_{be} = \frac{f_r}{2}N_b\left(1 - \frac{d}{Dm}\cos\alpha\right) \quad \text{..................(2)}$$

$$f_{bi} = \frac{f_r}{2}N_b\left(1 + \frac{d}{Dm}\cos\alpha\right) \quad \text{....................(3)}$$

$$f_b = \frac{f_r Dm}{2d}\left\{1 - \left(\frac{d}{Dm}\cos\alpha\right)^2\right\} \quad \text{...............(4)}$$

where f_c is the cage defect frequency, f_{bi} is the inner race defect frequency, f_{be} is the outer race defect frequency, f_b is the ball/roller defect frequency, d is the ball/roller diameter, Dm is the pitch diameter, N_b is the number of balls, and α is the ball contact angle (zero for rollers).

An appropriate frequency investigation of the vibration signal in Zone 2 prompts the learning of the amplitude of the frequency parts of vibration signal that are identified with bearing faults [Eqs. (1)– (4)],where a frequency segment at f_c, f_{bi}, f_{be} or f_b show up on the off chance that the comparing faults happens.

1.2 RESPONSE SURFACE METHODOLOGY

By careful design of experiments, the goal is to improve a response which is impacted by a few autonomous or independent factors. An examination is a progression of tests, called runs, in which changes are made in the input factors so as to recognize the purposes behind changes in the yield response. The utilization of RSM to plan enhancement is gone for decreasing the cost and time of investigations and its costly investigation technique.

Response surface methodology emerged in the mid fifty's for developing observational models of chemical engineering. RSM utilizes quantitative information from proper researcher about, to build up and simultaneously resolve multi-variable equations. That multi variable equation encourages us to assess the impact of independent factors and optimize the procedure parameters according to desired variable response. In the present work, RMS is likewise utilized for searching powerful input parameter as per required output.

Linear model of RSM shows relation between independent variable and output response.

$$y = a_0 + \sum_{i=1}^{n} a_i x_i \quad \text{..(5)}$$

A second-order model can altogether enhance the improvement procedure when a first-order model suffers absence of fit because of association amongst factors and surface curvature. A general second order model is characterized as,

$$y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_i {x_i}^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij} x_i x_j \quad \text{......(6)}$$

Where x_i and x_j are the design variables or independent variables and y is the dependent or output parameter and a are the tuning constants.

The development of a quadratic response surface model in N factors requires the examination, at three levels with the goal that the tuning parameters can be assessed. Subsequently, in any event [(N+1) (N+2)/2] function assessments are vital. For the most part, for an extensive number of factors, the quantity of examinations develops exponentially (3N for a full factorial) and winds up unrealistic.

In present work full factorial plan is utilized.

2. LITERATURE REVIEW

Issam Attoui et al. [1] present another methodology keeping in mind the end goal to recognize, distinguish and order diverse bearing shortcoming conditions, for example, an outer race defect, ball defect and inner race defect at various shaft turn speed (1730, 1750, 1772 and 1797 rpm) and for various defect conditions (0.007 in., 0.014 in. also, 0.021 in. holes).The proposed methodology is create by utilizing WPD and STFT. **Pankaj Gupta et al. [2]** compress the current patterns in inquire about on vibration examination of defects in moving component bearing and procedures for fault recognition in time, frequency and time frequency domain. Researchers have built up a few strategies for estimating vibration are as yet endeavoring to enhance signal processing techniques. **C. Mishra et al. [3]** summarizes three unique models of rolling elements bearing, to be specific, a 5-DOF demonstrate/model in MATLAB-Simulink condition, a bond graph model and a model in MBS programming ADAMS are created and approved with tests. These models would thus be able to fill in as information generators for improvement and testing of bearing fault diagnostic tools. **Patil M.S. et al. [4]** studied that the nearness of imperfection in the bearing outcomes in expanded vibrations. Time domain files, for example, rms, peak factor, and kurtosis were a portion of the vital parameters used to monitor the state of the bearing with RSM, he has built up the model with Kurtosis. **Choudhury et al. [5]** proposed rotor-bearing framework demonstrate which predicts critical segments at the harmonics of characteristic defect frequency for an imperfection on the specific bearing component. **J.P. Patel et al. [6]** summarizes full factorial strategies use to lead tests for exploring the synchronous impact of localized defects. Trials are additionally intended for consolidated defects in roller &inner race, inner race and outer race and inner race - roller and outer race. RSM is utilized to check the consolidated impact of RPM, Load and defect sizes on inner race, outer race and roller. **Gallina et al. [7]** explained response surface technique (RSM) is used to investigate the impacts of design and operating parameters on the vibration signature of a Rotor bearing framework. Distributed defects are viewed as, for example, internal radial clearance and surface waviness of the bearing parts.

From the relevant literature review on vibration detection and examination in rolling ball bearings, it is seen that no exertion has been made on applying RSM for single row ball bearings. The present examination, distinguish the impacts of localized defects on amplitude of vibration utilizing Response surface methodology (RSM) with the combined impacts of these defects on the single row ball bearing. This work endeavors to analyze vibration responses of a rotor-bearing system upheld on single row ball bearing.

3. EXPERIMENTAL SETUP AND METHODOLOGY

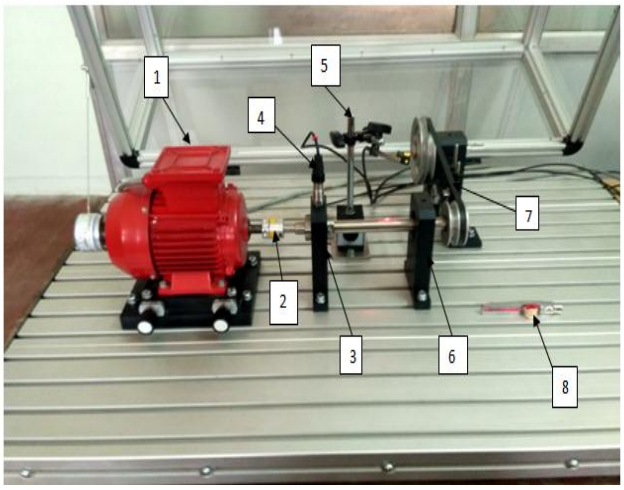

Fig-3. Experimental Setup in the laboratory

(1) Induction motor (2) Elastic Claw Coupling (3) Bearing block with non defective bearing (4) Acceleration sensors (5) Reference sensor with magnetic clamp (6) Bearing block with defective bearing (7) V belt with driving and driven pulley (8) Belt Pre-tension measuring device

In the experimental setup, the induction motor is used to drive the motor shaft at the desired speed, the motor shaft is coupled with short shaft with the help of elastic claw coupling. The short shaft is supported with the two bearing in which one is non defective and another one is defective and also used acceleration sensor to measure the vibration signal in either horizontal or vertical direction which is generally fitted over the bearing block. The reference sensor is used to measure the shaft speed. V belt drive is used to apply the radial load on the bearing and also belt pre-tension measuring device is used to measure the belt pre tension. Geometric specification of ball bearing SKF 6204 are listed in table (1).

Table -1: Geometric specification of ball bearing SKF 6204:

D_1	Outer dia of bearing	42 mm
D_2	Inner dia of bearing	20 mm
D	Ball diameter	6.35 mm
D_b	Pitch diameter	31 mm
N_b	Number of balls	9
W	Width of bearing	12 mm
α	Ball contact angle	0^0

Table -2: Characteristics frequencies of bearing:

Speed(N)	**Defective frequency, Hz**		
rpm	**Outer race (f_{be})**	**Inner race (f_{bi})**	**Ball (f_b)**
800	47.7 Hz	72.3 Hz	62.4 Hz
1200	71.6 Hz	108.4 Hz	93.5 Hz
1600	95.4 Hz	144.6 Hz	124.7 Hz

Table 2 shows Different frequencies for outer race, inner race and rolling element/ball are calculated by considering different speed conditions.

The RSM designs are ordered into central composite design and Full factorial 3 level. The present work utilizes full factorial 3 level presented outlines for three level factors that are generally utilized as a part of response surface techniques to fit second-order models to the response. The designs were created by the combination of two level factorial plans with incomplete block designs. The design is acquired by the combination of 22 plans with balance incomplete block design having three treatments and three block. The benefits of these designs incorporate the way that they are all spherical designs and expect variables to be keep running at just three levels and there are no runs where all elements are at either the +1 (highest value) or −1 (lowest value) levels. The design matrix intended for experimentation with the assistance of MINITAB programming with Full factorial 3 level and considering two factors. The factors are Load (in N) and Speed (in rpm). Factor and their level are given in Table 3, design matrix and their individual values are as given in Table 4.

Table-3: Factor and their level:

Factors	Notation	Values or Levels Coded		
		-1	**0**	**+1**
Speed(rpm)	N	800	1200	1600
Load(N)	W	70	100	130

Table-4: Design Matrix:

Run	Speed (rpm)	Load (N)	Velocity amplitude(mm/sec)	
			Inner	**Outer**
1	1600	100	0.253	0.193
2	1200	100	0.272	0.262
3	1200	100	0.272	0.262
4	800	130	0.241	0.202
5	1200	70	0.232	0.257
6	1200	100	0.272	0.262
7	1200	100	0.272	0.262
8	1600	70	0.242	0.219
9	1600	130	0.244	0.188
10	800	70	0.193	0.238
11	1200	100	0.272	0.262
12	1200	100	0.272	0.262
13	1200	100	0.272	0.262
14	1200	130	0.231	0.207
15	800	100	0.245	0.235

Then MINITAB software package is used to find out the following effects of above results with various graphs and statistical analysis. We have considered various things like main effects plot, contour plot and surface plot. These are as follows for outer race defect and inner race defect.

4. RESULT AND DISCUSSION:

4.1 RSM FOR INNER RACE DEFECT:

For inner race defect from the values as given in Table 5 we have got following results and plots.

Table-5: ANOVA table of Velocity Amplitude:

Source	Sum of squares	df	Mean Square	F-value	p-value	
Model	0.0068	5	0.0014	18.37	0.0002	Significant
A- speed	0.0006	1	0.0006	8.12	0.0191	
B- load	0.0004	1	0.0004	5.41	0.0450	
AB	0.0005	1	0.0005	7.16	0.0254	
A^2	0.0005	1	0.0005	6.68	0.0294	
B^2	0.0027	1	0.0027	36.54	0.0002	
Residual	0.0007	9	0.0001			
Lack of Fit	0.0007	3	0.0002			
Pure Error	0.0000	6	0.0000			
Cor Total	0.0075	14				

The Model F value of 18.37 implies the model is significant. There is only a 0.02% chance that an F- value this large could occur due to noise.
The p- value of model is less than the 0.005 implies the model is significant. In this case A, B, AB, A2 and B2 are the significant model terms and these values are less than 0.1 shown in Table 5.
The main effect plot (figure 4), contour plots and surface plots (figure 5) are as shown below.

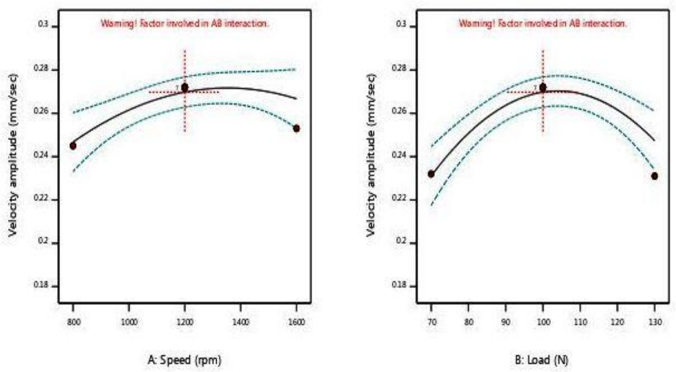

Fig-4: Main effect plot for inner race defect

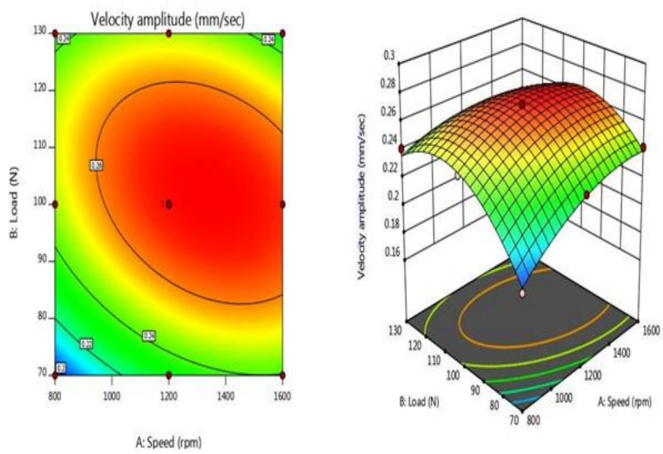

Fig-5: Contour and Surface plot for inner race defect

4.1 RSM FOR OUTER RACE DEFECT:

For outer race defect from the values as given in Table 6 we have got following results and plots.

Table-6: ANOVA table of Velocity Amplitude:

Source	Sum of squares	Df	Mean Square	F-value	p-value	
Model	0.0107	5	0.0021	22.35	<0.0001	Significant
A- speed	0.0009	1	0.0009	9.81	0.0121	
B- load	0.0023	1	0.0023	23.87	0.0009	
AB	6.250E-06	1	6.250E-06	0.0654	0.8039	
A^2	0.0036	1	0.0036	37.43	0.0002	
B^2	0.0009	1	0.0009	8.93	0.0152	
Residual	0.0009	9	0.0001			
Lack of Fit	0.0009	3	0.0003			
Pure Error	0.0000	6	0.0000			
Cor Total	0.0115	14				

The Model F value of 22.35 implies the model is significant. There is only a 0.02% chance that an F- value this large could occur due to noise.
The p- value of model is less than the 0.005 implies the model is significant. In this case A, B, AB, A2 and B2 are the significant model terms and these values are less than 0.1 shown in Table 6.
The main effect plot (figure 6), contour plots and surface plots (figure 7) are as shown below.

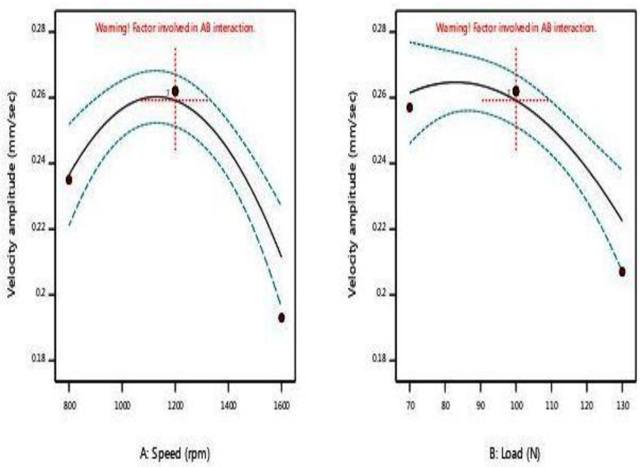

Fig-6: Main effect plot for inner race defect

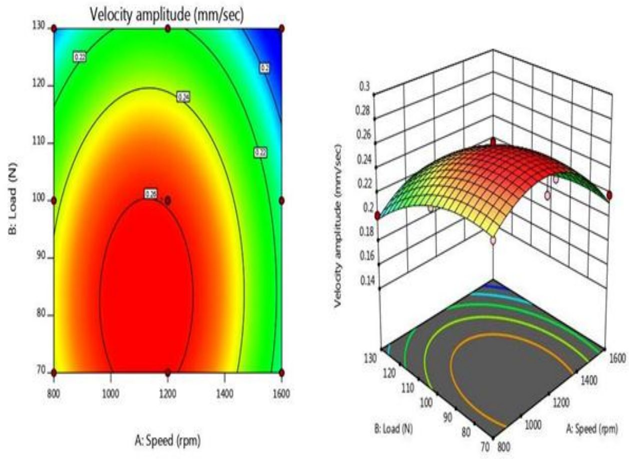

Fig-7: Contour and Surface plot for outer race defect

3. CONCLUSIONS

In this work, Full factorial methods are employed for detecting the simultaneous effect of localized faults in single row ball bearing. RSM is used to observe the combined effect of load and speed on the inner race and outer race. In case of inner race fault, the magnitude of velocity amplitude increases with increasing the speed while the magnitude of velocity amplitude initially increases with increasing radial load then its magnitude decreases with increasing load. In case of outer race fault, the magnitude of velocity amplitude initially increases with increasing speed then its magnitude decreases with increasing speed while the magnitude of velocity amplitude decreases with increasing radial load.
Ssurface plots shows the optimum conditions and values of independent parameters.

ACKNOWLEDGEMENT

We are thankful to the Department of Mechanical Engineering of MANIT, Bhopal, India for providing the necessary facilities for the successful completion of this work. Also pleased to acknowledge the support of MHRD for providing financial assistance during the tenure of M.tech at MANIT, Bhopal.

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