Resistive Lubricant Film Thickness for Ball Bearing 6307 using Design of Experiment for Elliptical Contact Area between Ball & Races

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Abstract

Experimental investigation on rolling element bearing with SAE 40 lubricating oil is tested for resistive lubricant film thickness (RFT). Bearing 6307 is tested for different combination of load and the speed with the help of Design of experiment (DOE) in order to save the time and cost of experimentation and also to determine the effect of each parameter. Result were obtained as per the planned experiment. The obtained result were analysed with main effect plot, cube plot and analysis of variance (ANOVA) using minitab statistical software.

Keywords: Resistance; Complete elliptical integral of second kind; Design of experiment (DOE); Elliptical contact area; Elliptical Parameter; General full factorial design; Hertz contact area; Rolling element bearing; Resistive lubricant film thickness (RFT); 2-level factorial design.

INTRODUCTION

Rolling element bearings are key elements of machineries parts, whose sudden failure can damage the system to uncorrectable level. Failure of system can lead to severe economic loss, its monitoring is very essential to avoid premature failures. Interferometry, vibration, acoustic emission, ultrasound, resistance and capacitance are the techniques for monitoring and diagnose the rolling element bearing, which attracted the researcher to explore. Observation of lubricant film thickness is one of the technique to avoid the failure of bearing. Lubricant film thickness depends upon the load and speed of the shaft on which the bearing is mounted. Roy Chowdhury [1] proposed a method for online condition monitoring and control of hydrodynamic journal bearing using film thickness measurement such that an adequate film thickness is maintained at all times. Prasad [2] have used a theoretical approach to determine the equivalent bearing capacitance, active resistance and impedance of roller bearing on deformation of races, minimum film thickness, lubricant characteristics and bearing geometry. Prasad [3] has observed the effects of operating parameters on the threshold voltages and impedance response of non-insulated rolling element bearings under the influence of varying levels of electrical currents. And established the voltage-current relationships in the bearings. He has also assessed the film thickness by the measured impedance and current intensity response of the bearings. Prasad [4] reports the cause of generation of localized current in presence of shaft voltage. Also, it bring out the developed theoretical model to determine the value of localized current density depending on dimensional parameters, shaft voltage, contact resistance, frequency of rotation of shaft and rolling-elements of a bearing. Jie Zhang [5] described a lubricant film monitoring system for a conventional deep groove ball bearing using high frequency ultrasonic transducer mounted in a hole drilled on the static outer raceway of the bearing. The film thickness is calculated using the reflection coefficient characterized by lubricant film. Bruce [6] measured the lubricant-film thickness in a rolling element bearing using a piezoelectric thin film transducer to excite and receive ultrasonic signals. High frequency (200 MHz) ultrasound is generated using a piezoelectric aluminum nitride film deposited in the form of a very thin layer onto the outer bearing raceway of a deep groove 6016 ball bearing. The reflection coefficient from the lubricant layer is then measured from within the lubricated contact and the oil-film thickness extracted via a quasi static spring model. M. S. Patil [7] has studied the influence of defect size, load and speed on the bearing vibration using Response Surface Methodology (RSM) using the statistical software MINITAB.

Hertz in 1881 [8] derived an analytical model for concentrated contact between two isotropic, homogeneous, linear elastic solids with smooth surfaces. He defined an elliptic parameter \( k \), the ratio of semi major axis to semi minor axis also given the formula for minor axis, major axis & equivalent modulus of elasticity. Harris [9] has given the elliptical para parameter \( k \) in the form of transcendental equation relating the curvature difference and the elliptical integrals of the first \((F)\) and second \((E)\) kinds. Brewe et.al [10] has given the simplified solution of elliptic contact, elliptic integral of first & second kind and elliptical contact deformation using the linear regression by the method of least squares. He found the simplified equations enable to calculate easily the elliptical-contact deformation to within 3 percent accuracy. Hamrock and Brewe [11], [12] used a linear regression by the method of least squares to power fit the set of pairs of data \([ (k_i, \alpha_i), i = 1, 2, \ldots, 26]\) and obtained the simplified solution for elliptical parameter \( k \). Greenwood [13], [14] compares their ‘Effective radius’ approximate method of finding the area of contact, the contact pressure and the deformation in elliptical Hertzian contacts with approximate methods of Brewe & Hamrock [10], and Hamrock & Brewe [11]. He concluded for \( 1 \leq (B/A) \leq 5 \) the Effective Radius method gives the best value for the Hertz pressure. Nijenbanning et.al.[15] used the multilevel solver for elliptical contact problem. He also studied the variations of film thickness with varying operating conditions and aspect ratio of the contact ellipse. He has given the formula that predicts the central film thickness as a function of load and lubricant parameters, and the
ratio of reduced radii of curvature of the surfaces. He concluded this formula incorporates asymptotic behavior so it is valid for all load conditions. D Jalali-Vahid et al. [16] given the numerical solution of isothermal elastohydrodynamic conjunction for concentrated contact of elastic bodies under the elliptical point contact condition. He includes effect of squeeze-film motion that occurs under transient conditions due to the application of cyclic loads and/or oscillating motions in machine elements in his solution. He concluded this time-dependent behavior increases the load-carrying capacity of the contact which is largely responsible as a mechanism of lubricant film formation when the low speeds of entraining motion yield a low film thickness. M. Kaneta et al. [17] has discussed the effects of thermal conductivity and kinematics of contacting surfaces and viscosity pressure coefficient on the film thickness in an elliptical contact under pure sliding conditions on the basis of experimental and numerical results. I. Křupka et al. [18] has given the experimental results at high contact stresses and low speeds to study the thin film behavior. They have observed ultrathin lubricant films at maximum Hertz pressures of 0.52, 1.01, and 1.54 GPa by using an optical test rig. They have also observed the nonlinear behavior of both central and minimum film thicknesses with rolling speed. They concluded slope of the film thickness decreases at higher speed.

Matharu et al. [19-24] have developed a new monitoring technique to measure the Resistive lubricant film thickness of Rolling Element Bearings. According the Hertz contact theory [9], [25] when the two isotropic, homogeneous, linear elastic solids with smooth surfaces solids are pressed together with a force \( Q \) directed normal to the surfaces, an approximately elliptic contact area is formed. Matharu et al. [19-24] has concentrated on studying circular contacts area. However, elliptical contact area in ball bearings, are likely to be of more practical importance. So this paper extends the circular model developed by Matharu et al. [19-24] to an elliptical geometry. In this paper the Resistive lubricant film thickness has been calculated by the analogy given by Matharu et al. [19-24] assuming the contact area to be Elliptical. The elliptical contact area has been calculated here for the bearing 6307 by Hertz contact theory. Correspondingly the Resistive film thickness has been calculated for lubricant SAE 40. And the variation of Resistive lubricant film thickness with load and speed is analyzed graphically and by 2-level factorial design of Design of experiment (DOE) [7], [26]. Number of researchers have also developed the techniques to monitor the lubricant film thickness, based on some parameters, by various methods [8], [10-16]. Either they are expensive or some major modification was required on the bearing for proper instrumentation. The present work uses the technique which is simple \& inexpensive [19-24]. Using this inexpensive technique Dewangan et al. [28-32] has done the work on resistive lubricant film thickness (RFT) for the different ball bearings and also calculated the electrical resistivity of the lubricants.

In the present work bearing 6307 \& lubricant SAE 40 is selected for the experimentation. For the measurement of the RFT, the experimental setup has been developed. The setup developed is inexpensive and easier to handle. Two parameters Load and Speed has been chosen for taking the reading of Voltage Drop between the ball and race of the bearing. Readings of the Voltage drop of the lubricant is taken at the Load of 40 kg, 60 kg, 80 kg \& 100 kg and at the Speed of 800 rpm, 1000 rpm, 1200 rpm \& 1400 rpm. RFT has calculated by Eq.(1). This equation includes the parameter Contact area of ball \& race, Resistivity of the Lubricant \& Bearing Resistance. For Resistivity of the lubricant separate experiment has been performed and Resistivity of lubricant SAE 40 has been calculated [24]. Experiment is planned by General full factorial design of Design of experiment on statistical software Minitab16 to improve the result. The 2-level factorial design of DOE in the software Minitab16 is performed to know the significant factors for the RFT. Normal probability plot, Pareto chart has plotted to know the significant factors. The p-value also indicates the significant factors. The Residual plot has plotted to know the data has fitted by DOE model are correctly or not. The Main Effect Plot and Interaction Effect Plot has also plotted to know the variation of RFT with the factors Load, Speed, Volt \& Bearing Resistance.

**Basic Term**

**Factors-** Factors are the variables used in the experimentation that influences the response or output.

**Level-** Level is the specific values for the factors at which the experiment is performed. The low and high levels of the factors may be in a coded scale or un-coded scale.

**Factorial design-** Factorial design is a tool to study the effects of several factors on a response. The interactions between the factors can also be studied with the factorial design.

**Effect-** The change in the response produced by a change in the level of the factor is called effect.

**Resistive Lubricant film thickness (RFT)-** It is an indicative lubricant film thickness formed between the heaviest loaded ball and race of the ball bearing.

**METHODOLOGY**

For a ball bearing, the Resistive lubricant film thickness (RFT) can be estimated by the formula given by Matharu et. al [19-23] is expressed below.

\[
(h_o)_T = \frac{a_1 a_2}{(a_1 + a_2)} R_T \rho
\]

Where,

\[
R_T = R_{IR} + R_{OR}, \quad R_{IR} = \frac{\rho h_o}{a_1}, R_{OR} = \frac{\rho h_o}{a_2}
\]

The contact area between the inner \& outer race with the balls are assuming to be elliptical, which has been calculated by the formula mentioned below.
Elliptical Area

The elliptical contact area at inner race and outer race for the calculation of Resistive film thickness can be calculated by given formula:

\[ a_1 = \pi \times a_i \times b_i \quad \text{&} \quad a_2 = \pi \times a_i \times b_i \]

where

\[ a_i = \left[ \frac{6\varepsilon QR}{\pi k E'} \right]^{\frac{1}{3}} \quad \text{&} \quad b_i = \left[ \frac{6k^2\varepsilon QR}{\pi E'} \right]^{\frac{1}{3}} \]

The parameters involved in the above can be calculated as follows

\[ \frac{1}{R_x} = \frac{1}{r_{ax}} + \frac{1}{r_{bx}} \quad \text{&} \quad \frac{1}{R_y} = \frac{1}{r_{ay}} + \frac{1}{r_{by}} \]

\[ \varepsilon = 1 + \left( \frac{q_a}{a} \right), \quad q_a = \left( \frac{\pi}{2} \right) - 1, \quad a = \frac{R_y}{R_x} \quad \text{&} \quad k = \left( a \right)^{2/3} \]

\[ \frac{2}{E'} = \frac{1 - v_x^2}{E_1} + \frac{1 - v_y^2}{E_2} \]

Bearing Resistance

Bearing Resistance for the calculation of RFT is calculated by the given formula:

\[ I = \frac{(V_{in} - V) \times 1000}{R_k} \quad \text{&} \quad R_T = \frac{V}{I} \]

On the basis of above formula, different parameter for elliptical area and RFT has been calculated for the Bearing 6307 and Lubricant SAE 40.

EXPERIMENTAL SETUP

A rolling element test rig is designed and set up to fulfill the requirements of the current investigation. The schematic of the test rig is shown in Fig. 1. The testing involves mounting and running the bearing under various speed and load conditions.

The test rig consists of seven major parts i.e. D.C. Motor, storage oscilloscope, variable A.C. transformer, regulated D.C. supply, electrical circuit, spring balance, non conducting tachometer and supporting shaft with the test bearing. The operational speed range is up to 1400 rpm and load range is up to 100 kg. One end of the supporting shaft is supported by two bearings and is coupled with the D.C. motor through rectifier and the other end is provided with an arrangement for radial load to be applied and also for bearings of different sizes to be attached. Storage oscilloscope, spring balance and non conducting tachometer are used to take observation while conducting the test run.

ANALYSIS & RESULT

Data has been collected by experimentation and reading of Voltage drop is used for the calculation of the Bearing Resistance and this is further used to calculate the RFT. Then, analysis of the data is done in two ways namely:

1. Calculation & Graphical Representation
2. Analysis by Design of Experiment (DOE) [26] by Statistical Software Minitab16

**Table 1:** Parameters for calculation of Elliptical Contact Area

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>BEARING 6307</th>
</tr>
</thead>
<tbody>
<tr>
<td>INNER RACE</td>
<td>OUTER RACE</td>
</tr>
<tr>
<td>(1/R_x)</td>
<td>0.19</td>
</tr>
<tr>
<td>(1/R_y)</td>
<td>0.0057</td>
</tr>
<tr>
<td>(R_x)</td>
<td>5.17</td>
</tr>
<tr>
<td>(R_y)</td>
<td>175.5</td>
</tr>
<tr>
<td>(1/R = (1/R_x)+(1/R_y))</td>
<td>0.1993</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>(R_y / R_x)</td>
</tr>
<tr>
<td>(k = (\alpha)^{2/3})</td>
<td>9.44</td>
</tr>
<tr>
<td>(q_a = (\pi/2) - 1)</td>
<td>0.57</td>
</tr>
<tr>
<td>(\varepsilon = 1 + (q_a / \alpha))</td>
<td>1.02</td>
</tr>
<tr>
<td>(E' (N/mm^2))</td>
<td>227363</td>
</tr>
</tbody>
</table>
Analysis by Graphical Representation

Variation of Resistive lubricant film thickness with speed, load, Bearing Resistance & Voltage for elliptical contact area are shown in Fig. [2-5].

**Figure 2:** Variation of Resistive Film Thickness (RFT) with Speed

**Figure 3:** Variation of Resistive Film Thickness (RFT) with Load

**Figure 4:** Variation of Resistive Film Thickness (RFT) with Bearing Resistance

**Figure 5:** Variation of Resistive Film Thickness (RFT) with Voltage

**Result**

Graphical analysis gives the following result:

1. It is seen in the Fig. 2 that for constant Load RFT increases with increase in Speed. Reason being, at higher speed the more lubricant is pushed in between ball & races due to wedging action.

2. It is observed in the Fig. 3 that for constant Speed RFT decreases with increase in Load. It is due to, at higher load the lubricant squeezed out of the contact area between ball & race and hence the RFT decreases.

3. From Fig. 4, it is observed that as Bearing Resistance increase, the RFT increases. It is seen from the Eq. 1 the Film Thickness is directly proportional to the Bearing Resistance. Also, the bearing resistance is more when the lubricant trapped is more i.e. the RFT is more.

4. From Fig. 5, it is observed that as the Voltage increases, the RFT increases. The voltage between the races will increase with increase in trapped lubricant between ball & races and with RFT.

**Analysis by DOE**

This analysis is done to know the individual effect and interaction effect of the factors. The \( p \)-value for the factors are calculated by the Minitab16 to know which factors are statically significant and which are not. The significance level is chosen 0.05 for the analysis. If the \( p \)-value comes \( \leq 0.05 \), then it can be concluded that the Null Hypotheses can be rejected and factor is statically significant i.e. factor has significant effect on the response. And if the \( p \)-value comes \( > 0.05 \), then it can be concluded that the Null Hypotheses cannot be rejected and factor is statically not significant i.e. factor has not significant effect on the response. The Null Hypotheses is assumed that the factors chosen for the analysis is insignificant, and the Alternative Hypotheses is assumed that the factors chosen for the analysis is significant. This analysis is also done to remove the unusual data.
In the present work DOE analysis is done for RFT as response factor for bearing 6307 & SAE 40 using the statistical software Minitab16 with the following details.

Type of Design : 2-Level Factorial
Confidence Level : 95 %
Number of Factors : 4 (Load-A, Speed-B, Volt - C & Bearing Resistance (R_T) - D)
Number of Level : 2 (Low & High)
Level Values :
- Load - 40 kg & 100 kg,
- Speed - 800 rpm & 1400 rpm,
- Voltage - 0.913 V & 0.984 V,
- Bearing Resistance (R_T) - 1049.43 kilo Ω & 6150.00 kilo Ω

Response: Resistive Lubricant Film Thickness (RFT)
Level of Significance (α): 0.05

Result

This analysis is done to know the individual effect and interaction effect of the factors Load, Speed, Voltage & Bearing Resistance on Resistive Film Thickness (RFT). The Normal Plot, Pareto Chart, Residual Plot, Main Effect Plot, Interaction Plot & Cube Plot are shown in Fig. [6-12]. Following result is obtained after the analysis:

1. It is observed from Fig.6 that the p-value for individual factors Load, Speed, Volt & RT and interaction of factors Load*Speed, Load*Volt, Load*RT, Speed*Volt & Speed*RT are 0.000, which is less than 0.05. Thus Null Hypotheses can be rejected and can be concluded that the all the factors and interaction of them are statically significant and Thus, these factors has statically significant effect on RFT.

2. It is also observed that the difference in calculated and predicted value of RFT is negligible and thus the percentage error. So, it can be concluded that the DOE fits the data well.

3. Normal Plot Fig.7 & Pareto Chart Fig.8 shows that the Load, Speed, Volt & R_T are significant and also the interaction of factors Load*Speed, Load*Volt, Load*RT, Speed*Volt & Speed*RT are significant for the RFT.

4. Residual Plot Fig.9 includes four plots namely Normal Probability Plot, Histogram, Residual Versus Fit & Residual Versus Order. All the four plots indicate no violation of statistical assumption. So, it can be concluded that the DOE model fits the data reasonably well.

5. The Main Effect Plot for 6307 & SAE 40 is shown in Fig.10. It indicates that the RFT increases with increase in the three factors Speed, Volt & R_T and decreases with increase in load.

6. The Interaction Plot of Load & Speed in Fig.11 shows that the RFT is high for lower Load. At lower Load the RFT increases rapidly with Speed, as the line for 40 kg is steeper than the 100 kg.

7. Cube Plot in Fig.12 shows that the RFT is maximum when the Load is 40 kg & the Speed is 1400 rpm, So it can be concluded that the RFT is maximum for lower load & higher Speed.

Figure 6: DOE Result for Resistive film thickness by Minitab16

Figure 7: DOE: Normal Plot for RFT
CONCLUSION

Following conclusion are drawn from the present work:

a. The graphical analysis of experimentation yields:
   1. The RFT increases with increase in speed for constant load due to more entrapment of lubricant owing to wedging action between ball and races.
   2. RFT decreases with increase in load which is analogous to the results of earlier researchers.

b. The DOE analysis yields:
   1. The individual & interaction effect of load, speed, voltage & bearing resistance were found to be statically significant for RFT.
   2. DOE as an effective tool for analysis of RFT is thus justified.

REFERENCE


