ANALYTICAL LUBRICANT FILM THICKNESS FOR PERFORMANCE EVALUATION OF BALL BEARING 6007, 6207, 6307 & 6407

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ABSTRACT

Rolling element bearings are one of the most essential parts of rotating machinery. The condition monitoring of rolling element bearing is very critical. Rolling element bearings rely on the formation of a separating oil film between surfaces having relative motion for their smooth operation and long life. The main purpose of lubrication is to enhance working life of bearing by reducing the friction between balls and races. Absence of this lubricant film is one of the most common reasons for bearing failure.

In the present work the lubricant film thickness is calculated by two methods first based on formula proposed by Archard and Kirk and second based on Hertz contact theory. The elastohydrodynamic lubricant film thicknesses (EHD) is calculated for bearings 6007, 6207, 6307 and 6407 for the four different lubricants. As the developed formula using Hertz contact theory for lubricant film thickness is dependent on different measurable parameters, so experiment can be performed and it can be used for online condition monitoring of rolling element bearings with very simple and inexpensive measuring instruments.

KEYWORDS: *Lubricant film thickness, Rolling element bearing, Viscosity, Condition monitoring, Eleastohydrodynamic lubrication (EHL), Resistivity.*

I. INTRODUCTION

Appropriate lubrication of rolling element bearings is essential for the proper functioning of the machine. A lubricant film separates the rolling elements of the bearing thus avoiding metal-to-metal contact, which may otherwise damage the bearing and lead to its failure. Therefore, estimation of the lubricant film thickness is essential for a reliable performance of the bearing. Different methods have been adopted by researcher to measure the lubricant film thickness. Smeeth et.al. [1] has used the interferometric method and measured the central and minimum elastohydrodynamic (EHD) film thickness at high contact pressure up to 3.5 GPa and compared the result with the classical film thickness equations of Hamrock and Dowson and also with the results of Venner. Zhang et.al.[2] has monitored failure of lubricant film using ultrasound and for this experiment was performed on deep groove ball bearing 6016. It has been concluded that the ultrasonic measurements are able to detect the failures before seizure. Drinkwater et.al. [3] also used the ultrasonic method to measure the lubricant film using a piezoelectric thin film transducer to excite and receive ultrasonic signals. An investigation was carried by Joyce et.al.[4] to study the reflection of ultrasonic waves from the lubricated contact between a sliding steel ball and a flat steel disc. Assuming a circular point contact the liquid film stiffness was calculated and predicted the film thickness and a bulk modulus. For contact pressures ranging from 0.42 to 0.84 GPa and sliding speed from zero to 2 m/s, the film thickness was found to vary from 0.01 to 0.8 µm. Electrical method including the measurement of electrical resistance and capacitance to determine the lubricant film thickness is discussed by Romeo et.al [5]. Wei Pu et.al. [6] has modified the mixed EHL model to consider the effect of arbitrary entraining velocity angle and found the good agreement with the previous literature. Mohammadpour et.al. [7] has given the solution of an elastohydrodynamic point contact condition using inlet and outlet lubricant entrainment with partial counter-flow and reported that the boundary condition used for the analysis is able to predict the pressure distribution between the ball to flat race contact. Matharu et.al [8-9] used the resistance method for online condition monitoring of the ball bearing. And lubricant film thickness was calculated by assuming the circular contact between the ball and races of the ball bearing. On the basis of data collected by experiment a new term critical viscous velocity is defined. Dewangan et.al. [10-11] used the Archard and Kirk's formula to measure the lubricant film thickness. And it is found that the formula used is applicable for analytical calculation of lubricant film thickness. Present work deals with the determination of the lubricant film thickness of lubricants designated as A, B, C and D based on Archard and Kirk's method and Hertz contact theory. The ball bearings 6007, 6207, 6307 and 6407 are considered for calculation.

In the present paper lubricant film thickness is discussed in the section methodology, sample calculation is done and the results are discussed. On the basis of calculation and results fruitful conclusions are taken also the future work is identified.

II. METHODOLOGY

Lubricant film thickness by Archard and Kirk method [12-13] includes the calculation of different non-dimensional parameters. The related formula is discussed below. The Hertz contact theory [13-14] is used to calculate the contact area between the ball and races of the ball bearing and further this is used for the evaluation of lubricant film thickness.

Archard and Kirk Method

Archard and Kirk [12-13] proposed the non-dimensional lubricant film thickness for ball bearing as given by

$$H_o = \frac{0.84\,(\gamma U')^{0.741}}{(Q')^{0.074}} \qquad or \qquad h_o = \frac{0.84\,(\gamma U')^{0.741}}{(Q')^{0.074}} \times R \tag{1}$$

$$\gamma = \lambda E', \quad E' = \frac{E}{1-\nu^2}, \quad U' = \frac{\eta_0 U}{2E'R}, \quad U = V_1 + V_2, \quad Q' = \frac{Q}{E'R^2}, \quad V_1 = \frac{\pi d_i N}{60}$$

$$\lambda = 0.1122\left(\frac{\nu_0}{10^4}\right)^{0.163}, \; \nu_o = 2.26 \text{ x } 10^{-3}(SSU) - \frac{1.95}{SSU}$$

Hertz Contact Theory

As the flow in the EHL contacts also affects the thickness of the lubricant layers on the track. The Hertz [13-14] derived an analytical model for concentrated contact between two isotropic, homogeneous, linear elastic solids with smooth surfaces. When the solids are pressed together with a force Q directed normal to the surfaces, an approximately elliptic or circular contact area is formed. Here it is assumed the circular contact area and calculated the contact radius. This is further used to calculate the EHD lubricant film thickness.

According to Hertz theory of elastic circular contact:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}, \qquad \frac{1}{E^*} = k_1 + k_2 \& \quad a = \left[\frac{3QR}{4\,E^*}\right]^{1/3} \tag{2}$$

$$k_1 = \frac{1-{\nu_1}^2}{E_1} \& k_2 = \frac{1-{\nu_2}^2}{E_2}$$

Applying this theory for rolling element bearing, we have

$$a_i = \left[\frac{3Q(k_1+k_2)r_i r}{4(r_i + r)}\right]^{\frac{1}{3}} \& a_o = \left[\frac{3Q(k_1+k_2)r_o r}{4(r_o - r)}\right]^{\frac{1}{3}} \tag{3}$$

Now, considering the bearing resistance between the ball and races of the bearing

$$R_{IR} = \frac{\rho\, h_o}{a_1} \& R_{OR} = \frac{\rho\, h_o}{a_2} \tag{4}$$

where

$$a_1 = \pi(a_i)^2 \& a_2 = \pi(a_o)^2 \tag{5}$$

Now, Total bearing resistance

$$R_T = R_{IR} + R_{OR} \tag{6}$$

Now, by equation 3, 4 & 5, we have

$$R_T = \frac{(a_1 + a_2)}{(a_1 a_2)} \rho\, (h_o)_T$$

So, EHD lubricant film thickness is given by

$$(h_o)_T = \frac{a_1 a_2}{(a_1 + a_2)} \frac{R_T}{\rho} \tag{7}$$

The present work deals with determination of lubricant film thickness of several lubricants for bearings 6007, 6207, 6307 and 6407. The comparison is made between the values of film thickness for all four bearings to validate of concept. The selected lubricants are designated as A, B, C and D. The viscosities of these lubricants for the calculation of film thickness are given in Table 1.

Table 1: Viscosities of the lubricants

Viscosity (η_o)	Lubricant A	Lubricant B	Lubricant C	Lubricant D
cP	111.23	173	287	348.75
N-s/mm^2	111.23 x 10^{-9}	173 x 10^{-9}	287 x 10^{-9}	348.75 x 10^{-9}
SSU	581.23	800	1330	1708.525

The main dimensions [15] of selected bearings 6007, 6207, 6307 and 6407 for analysis are given in Table 2. The dimensions are in mm.

Table 2: Useful dimensions of bearing

BEARING	r_i	r_o	r	R_i	R_o	d_i	d_o
6007	20	28.5	4.25	3.505	4.994	40	57
6207	21	32.5	5.75	4.514	6.986	42	65
6307	22	35.5	6.75	5.165	8.335	44	71
6407	23	44.5	10.75	7.326	14.174	46	89

III. ANALYSIS AND CALCULATIONS

Archard and Kirk Method

Analysis and calculations for lubricant A and ball bearing 6207 are shown. Values of parameters for other lubricants (B, C, and D) and ball bearing 6207 and lubricants (A, B, C, and D) and ball bearing 6007, 6307 & 6407 are also calculated similar to the calculations for lubricant A, which are not shown in the paper. The total lubricant film thickness for all the lubricants and bearings 6007, 6207, 6307 and 6407 are shown in Table 3.

Lubricant A

$$\nu_o)_{A6207} = 2.26 \text{ x } 10^{-3}(581.23) - \frac{1.95}{581.23} = 1.31022$$

$$\lambda)_{A6207} = 0.1122\left(\frac{1.31022}{10^4}\right)^{0.163} = 0.026128$$

$$\gamma)_{A6207} = 0.026128 \text{ x } 227363 = 5940.73$$

$$U')_{A6207} = \frac{111.23 \text{ x } 10^{-9}\frac{\pi d_i N}{60}}{2 \text{ x } 227363 \text{ x } R} = 1.28076 \text{ x } 10^{-14}\frac{d_i N}{R}$$

$$(\gamma U')_{A6207} = 5940.73 \text{ x } 1.28076 \text{ x } 10^{-14}\frac{d_i N}{R} = 7.6086 \text{ x } 10^{-11}\frac{d_i N}{R}$$

$$Q')_{A6207} = \frac{Q}{227363 \text{ x } R^2} = 4.3982 \text{ x } 10^{-6}\frac{Q}{R^2}$$

Equation (i) for contact of ball with inner race is written as:

$$h_o)_{i(A6207)} = \frac{0.84\,(\gamma U')^{0.741}}{(Q')^{0.074}} \text{X } R_i$$

After substituting the values of different parameters, we get

$$h_o)_{i(A6207)} = 6.6485 \text{ x } 10^{-8}\frac{(R_i)^{0.407}(d_i)^{0.741}(N)^{0.741}}{(Q)^{0.074}}\ mm$$

Similarly, for contact of ball with outer race, equation (i) is written as:

$$h_o)_{o(A6207)} = 6.6485 \text{ x } 10^{-8}\frac{(R_o)^{0.407}(d_i)^{0.741}(N)^{0.741}}{(Q)^{0.074}}\ mm$$

Total lubricant film thickness is:

$$h_o)_{T(A6207)} = h_o)_{i(A6207)} + h_o)_{o(A6207)}$$

$$= 6.6485 \text{ x } 10^{-8}\left[(R_i)^{0.407} + (R_o)^{0.407}\right]\frac{(d_i)^{0.741}(N)^{0.741}}{(Q)^{0.074}}\ mm$$

Substituting the values of R_i, R_o and d_i for bearing 6207, we get, total lubricant film thickness as:

$$h_o)_{T(A6207)} = 4.2983 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}\ mm$$

The formula for total lubricant film thickness is derived for lubricant B, C and D and ball bearing 6207 and also for lubricant A, B, C and D and ball bearing 6007, 6307 and 6407 similar to that derived for lubricant A.

IV. RESULT

Archard and Kirk's lubricant film thickness, as is clearly seen from the derived formula, is directly proportional to speed and inversely proportional to load. The film thicknesses calculated for lubricant A, B, C and D is tabulated in Table 3 for the bearings 6007, 6207, 6307 and 6407.

Table 3: Total Lubricant Film Thickness

Lubricant	$h_o)_T$ **in** mm			
	$h_o)_{T)6007}$	$h_o)_{T)6207}$	$h_o)_{T)6307}$	$h_o)_{T)6407}$
A	$3.6726\text{X}10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$4.2983 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$4.7438 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$5.8897 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$
B	$5.295\text{X}10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$6.1981 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$6.8405 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$8.4929 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$
C	$8.1944\text{X}10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$9.5912 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$10.585 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$	$13.1421 \text{ x } 10^{-6}\frac{(N)^{0.741}}{(Q)^{0.074}}$

D	$9.7588\text{X}10^{-6}\,\frac{(N)^{0.741}}{(Q)^{0.074}}$	$11.421 \times 10^{-6}\,\frac{(N)^{0.741}}{(Q)^{0.074}}$	$12.605 \times 10^{-6}\,\frac{(N)^{0.741}}{(Q)^{0.074}}$	$15.6504 \times 10^{-6}\,\frac{(N)^{0.741}}{(Q)^{0.074}}$

Hertz Theory

Analysis and calculations for ball bearing 6007 are shown. Values of parameters for ball bearing 6207, 6307 and 6407 are also calculated similar to the calculations for 6007, which are not shown in the paper. The total lubricant film thickness for all above bearings are shown in Table 4.

Bearing 6007

$$a_i = \left[\frac{3Q(k_1+k_2)r_i r}{4(r_i+r)}\right]^{1/3} = \left[\frac{3Q(4.398\,X\,10^{-6} + 4.398\,X\,10^{-6})20\,X\,4.25}{4(20+4.25)}\right]^{1/3} = 0.0285\,[Q]^{\frac{1}{3}}$$

$$a_i = \left[\frac{3Q(k_1+k_2)r_o r}{4(r_o-r)}\right]^{1/3} = \left[\frac{3Q(4.398\,X\,10^{-6} + 4.398\,X\,10^{-6})28.5\,X\,4.25}{4(28.5-4.25)}\right]^{1/3} = 0.0321\,[Q]^{\frac{1}{3}}$$

$$a_1 = \pi(0.0285)^2[Q]^{\frac{2}{3}} = 0.00255\,[Q]^{\frac{2}{3}}$$
$$a_1 = \pi(0.0321)^2[Q]^{\frac{2}{3}} = 0.00323\,[Q]^{\frac{2}{3}}$$

$$(h_o)_T = \frac{0.00255\,[Q]^{\frac{2}{3}}\,X\,0.00323\,[Q]^{\frac{2}{3}}}{\left(0.00255\,[Q]^{\frac{2}{3}} + 0.00323\,[Q]^{\frac{2}{3}}\right)}\frac{R_T}{\rho} = 0.00142\,\frac{Q^{2/3}\,R_T}{\rho}$$

Similarly, formula for total EHD lubricant film thickness is derived for ball bearing 6207, 6307 and 6407.

Result

It is clearly seen from the derived formula that EHD lubricant film thickness is directly proportional to load and bearing resistance and inversely proportional to resistivity of the lubricant. The film thickness calculated for bearing 6207, 6307 and 6407 are tabulated in Table 4.

Table 4 : EHD lubricant film thickness and other parameters

PARAMETER	$(h_o)_T$ in mm			
	6007	**6207**	**6307**	**6407**
a_i	$0.0285 \times Q^{1/3}$	$0.0310 \times Q^{1/3}$	$0.324 \times Q^{1/3}$	$0.0364 \times Q^{1/3}$
a_o	$0.0321 \times Q^{1/3}$	$0.0359 \times Q^{1/3}$	$0.380 \times Q^{1/3}$	$0.0454 \times Q^{1/3}$
a_1	$0.00255 \times Q^{2/3}$	$0.00302 \times Q^{2/3}$	$0.00330 \times Q^{2/3}$	$0.00417 \times Q^{2/3}$
a_2	$0.00323 \times Q^{2/3}$	$0.00404 \times Q^{2/3}$	$0.00454 \times Q^{2/3}$	$0.00647 \times Q^{2/3}$
$(h_o)_T$	$0.00142\,X\,\frac{Q^{2/3}\,R_T}{\rho}$	$0.00173\,X\,\frac{Q^{2/3}\,R_T}{\rho}$	$0.00191\,X\,\frac{Q^{2/3}\,R_T}{\rho}$	$0.00254\,X\,\frac{Q^{2/3}\,R_T}{\rho}$

V. CONCLUSION

From Table 3 it is clear that the total lubricant film thickness increases with viscosity of lubricant. Also the lubricant film thickness increases with increase in speed and decreases with increase in load. This is in-line with classical theory of lubrication [10]. The lubricant film thickness is function of speed and load on bearing. The method can be directly used for online condition monitoring of rolling element bearings with inexpensive instruments as speed and load can be easily measured during operation. A feedback control system can be used for continuous monitoring of lubricant film thickness with speed as controlling parameter.

From Table 4 it can be observed that the EHD lubricant film thickness is function of bearing resistance, resistivity of the lubricant and load on bearing. The lubricant film thickness increases with increase in load and bearing resistance and decreases with increase in resistivity of the lubricant.

The total EHD lubricant film thickness increases as the bearing number increases. Larger the size of the bearing, larger will be diameter of balls with more elastohydrodynamic contact area. The larger balls will have more lubricant entrapped than that with smaller balls to take up more load. The method can be directly used for online condition monitoring of rolling element bearings with the help of resistivity and bearing resistance measuring instruments and load can be easily measured during operation. It is found that the formula proposed using the Hertz contact theory is dependent of experimental data. So that the lubricant film thickness can also be calculated experimentally.

VI. FUTURE WORK

As seen in Table 4, the calculation done for the lubricant film thickness is analytically and it is found that the lubricant film thickness is dependent on the Bearing resistance, Load and Resistivity of the lubricant. An experiment can be performed to measure the Resistivity of the lubricant. Similarly a separate experiment can be performed to know the Bearing resistance at different loading conditions. The lubricant film thickness can be calculated at running condition so this method can be adopted for the online condition monitoring of the bearing.

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NOMENCLATURE

H_o - Dimensionless film thickness = h_o / R

H_o - Minimum film thickness (mm) = H_o x R

γ - Dimensionless elastic constant

U' -Dimensionless velocity

Q' - Dimensionless load

λ - Pressure coefficient of viscosity (mm^2/N)

ν - Poission's ratio = 0.3 (for steel)

η_o - Oil viscosity at atmospheric temperature (Ns/ $mm^{2)}$

U - Entrainment velocity (mm/s)

V_1 - Velocity of inner race (mm/s)

V_2 - Velocity of outer race (mm/s)

Q - Force acting on ball (N)

E - Modulus of elasticity (N/mm^2)= 206900 N/mm^2 (for steel)

r_i - Outer radius of inner race (mm)

r_o - Inner radius of outer race (mm)

r - Radius of ball (mm)

R_i - Equivalent contact radius of inner race (mm)

R_o - Equivalent contact radius of outer race (mm)

d_i - Contact diameter of inner race (mm)

a - Contact radius (mm)

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