SAFE LUBRICATION FOR HIGH SPEED BALL BEARINGS ASSEMBLIES

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SUMMARY

In given conditions of geometry, speed, loads and mounting arrangement the lubrication regime can be considered as one of the most important influence parameter of the ball bearings service life and, consequently, of the operating assembly reliability. A complex research program concerning the lubrication of the high speed ball bearings assemblies, considering the dynamic stability and thermal regime as main reliability parameters, was carried out and, for a grinding machine test spindle, in given operating conditions, the optimum lubricant was determined.

Keywords: high speed, ball bearing, lubricant, dynamic stability, thermal regime

1 INTRODUCTION

The bearing service life is decisively influenced by the reliability of its rolling/sliding tribosystems, i.e. ball/race, ball/cage, guided cage/race. In high speed operating conditions, the centrifugal effects, friction losses and, as result, the heat generated in all of these tribosystems, especially on the ball/race contacts, can drastically reduce the bearing service life. To design a high speed ball bearings assembly with enhanced qualitative performances, the securing of an efficient and safe lubrication regime, i.e. EHL conditions for all the bearings ball/race contacts during functioning, represents one of the most important condition. That means to realise and maintain a lubricant film thickness able to both completely and safety separate the ball/race surfaces in relative movement and, also, to take over an important heat part emitted in the contact zones under high Hertzian stresses [1-4].

According to the fatigue phenomenon the service life of a ball bearing, in a given application, is determined, in most of cases, by the ANSI/AFMBA Standard life rating formula (1990) [5]:

\[ L_v = a_1 a_2 a_3 \left( \frac{C}{P} \right)^3, \]  

(1)

where: \( L_v \) is the bearing service life in \( 10^6 \) revolutions corresponding to reliability level of \((100 - v)\); \( a_1 \) – reliability factor; \( a_2 \) – material factor; \( a_3 \) – lubrication-life factor; \( C \) – basic dynamic load rating; \( P \) – applied equivalent load.

The lubricant regime has a decisive influence on the bearings service life and, as result, various correction factors have been proposed to be included in the service life formula as: \( a_3 \) - Lundberg and Palmgren [6-7]; \( a_1 \) – FAG [8] with a range value of 0.5...3; \( a_3 \) and \( a_2 \) (considering, in addition, the contamination level) - Sayles and MacPherson [9]; \( a_{SKF} \) - SKF [10], considering the lubrication conditions, load and contamination level, with a range value of 0.1...50.

After many authors the ratio \( \lambda \) of the lubricant film minimum thickness to composite ball/race surface roughness can be considered as a tribological safety criterion of the high speed ball bearings functioning [5-7]. Ideal lubrication conditions and, consequently, maximum bearing service life can be obtained if, for all the ball/race contacts are secured values \( \lambda > 3 \). In agreement with the isothermal EHL theory [5-7] the speed or lubricant viscosity increase determines the lubricant film thickness increase. However, if these operational parameters overtake some limits, i.e. \( \lambda > 5 \), the operating temperatures increase due to lubricant film shear stresses, the film thickness decreases as result of both thermal and starvation phenomena, that act in interdependence and, consequently, the bearing service life decreases. On the other side, some recently researches highlighted a significant influence of the lubricant on the dynamic characteristics of high speed ball bearings: dynamic stability increase with the lubricant viscosity increase as result of the squeeze effects in the lubricant entry region of the ball/race contacts [11]. For high speed ball bearings assemblies-grinding machine spindles, for exemple- obtaining of a high dynamic stability could become, because of a high requested working accuracy, more important than a long service life and, consequently, the optimum lubricant must be choose according to this reliability factor [1-4]. By these considerations, it is obvious that a safe lubrication for high speed ball bearings assemblies is secured if this compromise, i.e. dynamic stability - thermal regime, can be solved by the choice of an optimum lubricant able to ensure, in the same time, an imposed ratio \( \lambda \) of the lubricant film minimum thickness.

2 LUBRICANT – DYNAMIC STABILITY

The vibration behaviour of a high speed spindle is mainly influenced by the dynamic characteristics of its component parts, i.e. shaft-bearings-housing. If the interfaces shaft/inner ring and housing/outer ring are carefully controlled and considered as "rigid joints", the bearing element interactions, and consequently, its rigidity and damping characteristics, especially of ball/race contacts, can be considered as having a major influence on the spindle dynamic state [1-4]. To design a high speed spindle with enhanced dynamic characteristics, i.e. low vibration levels and critical speeds located away from the running speed by a safe
margin in given operating conditions, as essential conditions for a high working accuracy, the designer must estimate and take into account, in a dynamic analysis, all of these characteristics; thus, a theoretical spindle dynamic state more nearly to the real one could be estimate and the failure risk should be more correctly predict.

Hagiu and Gafitanu [11] developed a complex analysis concerning the dynamic characteristics of high speed angular contact ball bearings. Thus, the dynamic mechanism of a high speed ball/race contact operating in EHL conditions (Fig. 1), considering the elastic deformation of the Hertzian contact, both squeeze and damping effects in the lubricant film and, also, the thermal and starvation effects on the lubricant film thickness is governed by:

* elastic rigidity \( k_c \) of the Hertzian elastic contact and the film rigidity \( k_{ef} \) in the inlet region of the Hertzian contact area acting in parallel and in phase with the displacement \( \delta \) on \( z \) direction;
* film damping \( h_{ef} \) in the inlet region of the Hertzian contact area acting in quadrature (\( u_{1,2} \) - speed of ball and race in rolling direction, respectively; \( Q \) - normal load on the contact).

\[ Q = \delta \left( k_{ef} + k_c \right) + i h_{ef} \]  

(2)

Consequently, the normal load on the contact is given by:

For an angular contact ball bearing loaded by a radial force \( F_r \), axial force \( F_a \) and bending moment \( M \) the relative displacement between rings has different components from each ball/race contact. Consequently, by summation of the normal loads on ball/race contacts the load-displacement correlations of the bearing are given by, respectively:

\[ F_{r,a} = \delta_{r,a} \left( K_{r,a} + i H_{r,a} \right) \quad M = \varphi \left( K_m + i H_m \right) \]

(3)

where: \( \delta_r, \delta_a, \varphi \) are the displacements between bearing rings on radial, axial and angular directions, respectively; \( K_r, K_a, K_m \) – the overall rigidities acting in phase with the displacements, respectively; \( H_r, H_a, H_m \) – overall dampings acting in quadrature, respectively.

By these assumptions, for a high speed angular contact ball bearing under a complex load, the dynamic model presented in Fig. 2 was proposed.

To emphasize the lubricant influence on the dynamic behaviour of high speed ball bearings assemblies a complex theoretical and experimental research concerning the dynamic stability of a grinding machine test spindle (Fig. 3) was achieved.
In these sense, the acceleration amplitudes of the transversal vibration of the offset grinding wheel in various conditions of preload $F_p$, speed $n$ and lubrication were determined, respectively. The results obtained for three oil types, i.e. Te14, H18 and M20 (Fig. 4), highlighted an improved dynamic stability for a higher viscosity (oil M20) as result of bearing damping increase due to a greater resistance to oil squeeze action in the entry region of the ball/race contacts. In addition, theoretical lubricant ratios $\lambda > 1.5$, determined considering, also, both thermal and starvation effects [6-7,11], were estimated for all the used oils.

3 LUBRICANT - THERMAL STABILITY

In high speed conditions the operating thermal regime of the bearings, that decide, in fact, the spindle thermal state, represents the result of some heat sources:

* viscous friction in lubricant film, i.e. shearing of lubricant as effect of sliding due to contact deformations or spin and gyroscopic motions as result of kinematics changes;

* intense local heating or cooling phenomena as result of speed variations, internal load distribution changes, lower efficiency of the sealing and cooling systems.

Thus, the spindle operating thermal regime shall be determined, to a great extent, by the amount of the heat transfer balls/races through the lubricant film. Bearing operating temperature increase implies important changes of the lubricant main parameters, especially on the dynamic and kinematics viscosity. Thus, it is very important to realise and maintain a low and stable thermal regime within bearing operating to avoid possible negative successive phenomena: lubricant viscosity decrease, bearing heating, scuffing as result of sudden collapses of the lubricant film, contact failure and bearing assembly out of order [12-15]. In high speed conditions the bearing balls and races operate at different temperatures that, furthermore, vary during functioning. Consequently, the bearing operating temperature is often adopted as a average value because it's very difficult to calculate or measure temperatures as different locations during functioning [16-18].

By these considerations, in the same operating and lubrication conditions, the average steady state functioning temperatures of the test spindle bearings were determined. The results obtained (Fig. 5) highlighted higher functioning temperatures for the oils with higher viscosity.

4 OPTIMUM LUBRICANT

For the test spindle, although the oil Te14 secures lower bearings functioning temperature in the given operating conditions, to obtain a high dynamic stability, the oil M20 should be recommended.

5 CONCLUSIONS

1. Dynamic and thermal stability, in the conditions of the securement of an imposed lubricant ratio $\lambda$, can be considered as important lubrication safety criteria in the functioning of the high speed ball bearings assemblies. Obviously, this task implies a complicate mathematical apparatus justified, however, by the high reliability and accuracy requirements imposed to the high speed spindles; in this case the results obtained could have a content nearly by the reality and, also, a supplementary thrust degree.

2. To secure a safe lubrication for a high speed spindle assembly, in given operating conditions, represents a difficult task for the designer mainly due to of two opposite effects that occur simultaneously:

Fig. 4: Vibration levels of the test spindle vs. speed $n$, bearings preload $F_p$, and lubricant type
* firstly, a higher oil viscosity will increase the 
  bearings damping derived from the ball/race contacts 
  due to an extra resistance to squeeze; 
* secondly, conversely, a higher oil viscosity will 
  increase the film thickness together with the contact 
  squeeze ability.

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Fig. 5: Average steady state functioning temperatures of 
 the test spindle bearings vs. speed n, bearings preload F_p 
 and lubricant type