Research procedure of radial clearances in rolling bearings

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Abstract. In the result of the rolling bearing research it has been found that the bearing radial clearance, especially with a small number \( z \) of rolling elements \( z<15 \) besides technological factors depends on the rolling element location in the bearing during measurement. During operation the simple rolling bearing design is characterized by complex dynamic processes. In theoretical mechanics general technical calculations are carried out for absolutely rigid bodies that are not deformed during the working load application. This position is completely used in design diagrams as the deformations of races and rolling elements are not taken into consideration. If the bearing is manufactured and operated with a nominally reasonable value of the radial clearance, then the probability of its successful operation will be very high. During the bearing manufacturing it’s necessary to take into consideration the radial clearance as a geometric parameter along with other dimensions of the bearing. Analytical expressions for the radial clearance calculation have been obtained for the first time for odd and even layouts of the rolling element location in the bearing operating area. The calculation results for definite bearings are given. The justification of initial clearances and creation of the analytical method for the radial clearance determination represent a crucial task of the rolling bearing theory.

Key-words: rolling bearing, radial clearance, geometrical parameters, number of rolling elements.

1. Introduction

The creation of modern highly efficient technological machines is connected with the usage of rolling bearings in transmissions and mechanisms. During the creation of new machines in various branches of mechanical engineering the necessity arises to change the design and increase the reliability of mechanism mounting groups.

Work [1] is known which is written by Meier Nicolas, Papadoudis Jan, Georgiadis Anthimos, who investigated the radial clearance measurement system in rolling bearings. The traditional concept of the radial clearance is applied. The compliance of the radial clearance value with the bearing operation durability is noted. Various methods for measuring bearing radial clearances are taken into consideration. Work [1] shows the relevance of rolling bearing clearance researches.

In work [2] the authors Meng Li, Mingqing Jing, Zengfan Chen, Heng Liu developed the measurement procedure of the lubricant film thickness in roller bearing clearances under high loads and low speeds aimed at increasing the durability and reliability of the roller bearing lubricant in industry. The ultrasonic method of the lubricant film minimum thickness measurement by a broadband ultrasonic probe has been considered. Work [2] confirms the research relevance of the rolling bearing radial clearances.
The following authors Govardhan T., Choudhury Achintya, Paliwal Deepak in their work [3] obtained the results of measuring the radial clearances in NJ204 bearing during the dynamic load application on the bearing, and received oscillation excitation spectra during various external loads induced by static and harmonic components.

In works [4-11] topical problems of rolling bearings are investigated.

2. Problem statement

The radial clearance is the main technical and operational characteristic of a rolling bearing, which is justified during engineering and monitored in operation. The radial clearance means the length of movement in the radial direction of the inner ring from one limit position to another. However, at present in the result of the research it has been established that in general the rolling bearing radial clearance value depends on the number of rolling elements in the bearing expressed by \( z \), on its loading, temperature, assembly conditions and other factors.

3. Theory

Figures 1 and 2 show the first design diagram for the analytical determination of the bearing clearances when one rolling element with the center at the point \( C \) is located under the bearing axis.

**Figure 1.** First design diagram with the even number of rolling elements \( z = 18 \) for the analytical determination of the radial clearances \( M_1M_2 = \delta_1 \) in the bearing.
Figure 2. First design diagram with the odd number of rolling elements \( z = 7 \) for the analytical determination of the radial clearances \( M_1M_2 = \delta_1 \) in the bearing.

In the process of the bearing manufacturing the dimensional check is carried out of its components in unloaded condition. In order to obtain stable results during experimental studies of radial clearances it is necessary to set the radial force of a small value of \( P = 0.005C_0 \) of the bearing nominal static load capacity.

Under actual operating conditions, elastic deformations caused by a radial load, temperature conditions and other factors which can be simulated by the analytical method exert influence on the bearing clearances.

For the determination of the radial clearance (see Figure 1) let’s move the inner ring mentally upwards for the coincidence of the centers \( O_2 \) and \( O_1 \) of the inner and outer rings. In this case the vertical movement of the \( O_1O_2 \) center of the inner ring will be \( O_1O_2 = \varepsilon \), which is equal to \( \varepsilon = 0.5G_r \), where \( G_r \) is the bearing radial clearance. With the further upward movement of the inner ring center from the \( O_1 \) position until the inner ring bumping into the upper ball, we obtain the complete movement \( 2\varepsilon \) equal to the clearance \( G_r = 2\varepsilon \). However, this known provision is true only for the even number of rolling elements shown in Figure 1.

In the operating area shown in Figures 1 and 2 the odd symmetric loading diagram of rolling elements in the operating area is applied, when the inner ring rests on one rolling element. Such loading diagram is true for the even \( z = 18 \) and odd \( z = 7 \) of the total number of the rolling elements [8, 9]. In accordance with the provision relative to absolutely rigid bodies at the point \( A \), the ball and inner ring maintain their nominal dimensions, that’s why in the diagrams (see Figure 1, Figure 2), only one central ball operates in the operating area, and for other rolling elements to the left and to the right the clearances with the \( M_1M_2 \) dimension appear with the inner ring, which can be determined analytically by the proposed method.

The bearing radial clearance depends on the nominal diameter \( F_w \) of the circumference, enveloping the inner surfaces of the rolling elements, pressed against the bearing outer ring race. The diameter \( F_w \) is determined by the formula

\[
F_w = D_1 - 2D_w, \tag{1}
\]

where \( D_1 \) is the diameter of the outer ring race; \( D_w \) is rolling element diameter.

The clearance \( G_r = 2\varepsilon \) according to Figure 1 is the difference between the enveloping circumference diameter \( F_w \) and diameter of the race inner ring

\[
G_r = F_w - d_1. \tag{2}
\]

At specified dimensions \( D_1, d_1 \), the radial clearance \( G_r \) is adjusted by the selective review of the rolling elements with the dimension \( D_w \).
The number of rolling elements – balls expressed by \( z \) depends on the circumference diameter \( d_m \), where the centers are located of all rolling elements and angle \( \varphi \) of filling the bearing race with balls, which is formed provided that all the balls are tightly arranged to each other on this circumference subject to the firm adjacency to the circumference with the outer diameter \( D_1 \). The ball filling angle is usually equal to \( \varphi = 186^\circ \) [7].

The number of rolling elements \( z \) of the bearing is determined by the formula

\[
z = \frac{0.5\varphi \pi}{180^\circ} + 1, \tag{3}
\]

where \( D_w \) is the ball diameter; \( d_m \) is the diameter of the rolling element center location in the bearing.

The result of the calculation by the formula (3) is rounded to an integer.

Permissible variations of the diameters of the races \( d_1 \) and \( D_1 \) are realized within the limits \( \pm 0.015 \text{ mm} \) [7]. The radial clearance \( G_r \) is formed in the result of the combination of the dimensions \( d_1, D_1 \) with the ball dimension \( D_w \) or other combinations of these dimensions.

During the mass production bearings are completed in such a way in order to ensure the required clearance \( G_r \), when the minimum resistance to the bearing rolling, minimum shaft oscillations and maximum durability (operational life) of operation at rated load are provided. The clearance \( M_1M_2 \) between the rolling element with the center \( C_1 \) and inner ring can be determined as follows (see Figure 1, Figure 2). Based on the triangle \( C_1K_2O_1 \) the length \( K_2C_1=0.5d_m \sin \gamma, \ d_m=0.5(d+D) \) is determined, where \( d, D \) are the inner and outer bearing diameters accordingly.

The angle \( \alpha \) is determined based on the triangle \( C_1K_2O_2 \)

\[
\alpha = \arctg \frac{K_2C_1}{K_2O_2} = \arctg \frac{0.5d_m \sin \gamma}{0.5d_m \cos \gamma - 0.5G_r}. \tag{4}
\]

Let’s determine the angle \( \alpha_1 \) according to the formula \( \alpha_1 = \alpha - \gamma \).

The clearance amount \( M_1M_2=\delta_1 \) is determined from the equation of the projections of the triangle side lengths \( C_1O_2O_1 \) on the line \( O_1C_1 \) according to the equation

\[
\delta_1 = \frac{0.5d_m - 0.5G_r \cos \gamma - 0.5d_1 \cos \alpha_1 - 0.5D_1 \cos \alpha_1}{\cos \alpha_1}. \tag{5}
\]

### 4. Results discussion

The ball bearing 1000917* has the following parameters: number of rolling elements \( z = 18 \); outer diameter \( D = 120 \text{ mm} \); internal diameter \( d = 85 \text{ mm} \); diameter of the rolling element center location in the bearing \( d_m = 102.5 \text{ mm} \); rolling element diameter \( D_w = 9.53 \text{ mm} \); diameter of the outer ring race \( D_1 = 112.03 \text{ mm} \); diameter of the circumference, enveloping the inner surfaces of rolling elements \( F_w = 92.97 \text{ mm} \); static load capacity \( C_0 = 30 \text{ kN} \).

Table 1 shows the research results of the bearing 1000917* according to the first design diagram.

| Ball bearing parameters | Ball bearing characteristics with the conventional radial clearance \( G_r \) (mm), equal to |
|-------------------------|-----------------------------------------------|
| Diameter of internal ring race \( d_1 \), mm | 0.05 | 0.1 | 0.15 | 0.20 |
| 92.92 | 92.87 | 92.82 | 92.77 |
| Angle \( \alpha \), grad | 20.0095636 | 20.0191359 | 20.028717 | 20.0383069 |
| Angle \( \alpha_1 \), grad | 0.0095636 | 0.0191359 | 0.028717 | 0.0383069 |
| Clearance \( M_1M_2=\delta_1 \), mm | 0.001508398 | 0.003018225 | 0.004529482 | 0.006042171 |

The calculated clearance values \( \delta_1 \) correspond to an unloaded bearing when the force \( P=P_{\min} \).
the nominal load $P = C_0$ is applied on the bearing the deformation of the central ball $C$ occurs, and in the result of an additional lowering of the inner ring the clearance $\delta_1$ disappears and elastic deformations occur in other balls.

The design diagrams in Figure 3, Figure 4 are shown for the second layout of the rolling element location in the operating area. In the bearing operating area on the bottom two rolling elements operate with the centers at points $C_1$ and $C_2$.

**Figure 3.** Second design diagram with the odd number of rolling elements $z = 7$ for the analytical determination of the bearing shaft axis subsidence $\varepsilon_1$.

**Figure 4.** Second design diagram with the even number of rolling elements $z = 18$ for the analytical determination of the bearing shaft axis subsidence $\varepsilon_1$. 
For the even number of rolling elements in the bearing operating area the second kinematic design diagram of radial clearances in rolling bearings is applied [8, 9].

In Figure 3, Figure 4 the inner race with the shaft rests on two rolling elements in a lower position. If we conventionally perform the inner ring with the diameter $d_1$ equal to the diameter $F_w$, then the $O_1$ and $O_2$ centers of the inner and outer rings will coincide and the clearance $G_1$ will be equal to zero.

In a real bearing the diameter $d_1$ is smaller than the diameter $F_w$ that’s why the clearance $G_1$ is formed, and the center $O_2$ of the inner ring with the shaft has the possibility to go down relative to the $O_1$ center for the $\varepsilon_{11}$ value (see Figure 3, Figure 4).

In the technical literature attempts are known to be made for the analytical determination of $\varepsilon_{11}$ value of lowering the $O_2$ axis of the bearing inner race. However, at the same time an imperfect design diagram is applied which doesn’t take into consideration the rolling element size $D_n$ and other factors.

In Figure 3, Figure 4 the triangle sides are determined by the formula $C_iC_2=d_n\sin0.5\gamma$, taking into consideration that $C_iO_i=C_2O_2=0.5d_n$, we determined $C_1O_2= C_iO_j= 0.5d_1+0.5D_n$.

The $\varepsilon_{11}$ value of lowering the inner ring axis relative to the $O_1$ center of the outer ring can be determined by the formula

$$\varepsilon_{11}=M_3O_1-M_1O_2. \tag{6}$$

For the solution of equation (6) we use the theorem of the height of the triangle tops [12], which for this particular case of symmetric triangles allows to determine the triangle heights according to three known sides without using trigonometric functions

$$M_3O_1 = \sqrt{\left(\frac{(C_1O_1)^2}{C_1C_2}\right)^2 - \left(\frac{(2(C_1O_2)^2-(C_1C_2)^2)}{2(C_1C_2)}\right)^2}. \tag{7}$$

$$M_3O_2 = \sqrt{\left(\frac{(C_1O_2)^2}{C_1C_2}\right)^2 - \left(\frac{(2(C_1O_2)^2-(C_1C_2)^2)}{2(C_1C_2)}\right)^2}. \tag{8}$$

5. Consideration of the results

Table 2 presents the research results of the bearing 1000917* according to the second design diagram.

| Ball bearing parameters                  | Ball bearing characteristics with the conventional radial clearance $G_i$ (mm), equal to |
|-----------------------------------------|-----------------------------------------------|
| Diameter of internal ring race $d_1$, mm | 0.05 0.10 0.15 0.20                               |
| Inner ring axis movement value with support on one central element $\varepsilon_{11}$, mm | 92.92 92.87 92.82 92.77                           |
| Inner ring axis movement value with support on two central element $\varepsilon_{12}$, mm | 0.025 0.05 0.075 0.10                             |
| Movement $M_3M_5= \delta= \varepsilon_{11} - \varepsilon_{12}$, mm | 0.025385858 0.050772101 0.076158731 0.101545747 |
| Movement $M_4M_5= \delta= \varepsilon_{11} - \varepsilon_{12}$, mm | 0.000385858 0.000772101 0.001158731 0.001545747 |

The $\varepsilon_{11}$ value of the shaft subsidence with the inner race in Figure 4, Figure 5 is determined by the formula (6).

The movement $M_3M_5$ is equal to the difference between the shaft subsidence $\varepsilon_1$ and rolling bearing eccentricity $\varepsilon$ according to the proposed procedure: $\delta=\varepsilon_{11}-\varepsilon$.

For Figure 3 with the odd number of rolling elements $z$ and Figure 4 with the even number $z$ of rolling elements, the total clearance $G_1$ is determined by different methods and has different values.

According to Figure 3 for the odd number $z$ of rolling elements the total clearance $G_1$ is composed of two movements: $1$ – downward movement of the inner ring measured from the $O_1$ position for the value of $\varepsilon_{11}$ with support on two rolling elements; $2$ – upward movement with support on one central
element upwards for the value of $\varepsilon$, i.e.

$$G_r = \varepsilon_1 + \varepsilon. \quad (9)$$

In Figure 4 for the even number $z$ of rolling elements the total clearance $G_r$ is composed of two movements: 1 – downward movement of the inner ring measured from the $O_1$ position for the value of $\varepsilon_1$ with support on two rolling elements; 2 – upward movement with support on two rolling elements also for the value of $\varepsilon_1$. Thus, with the even number $z$ of rolling elements for the second design diagram the total clearance is determined by the formula

$$G_r = 2\varepsilon_1. \quad (10)$$

During the bearing’s operation constant high-frequency changes of the radial clearance occur within definite limits with the pulsation frequency along the shaft rotation angle at a pitch of $\varphi = 0.5\gamma$, perceiving in the form of vibration and noise.

6. Conclusion

The design diagrams for the radial clearance determination have been developed in this paper for the first time taking into consideration all geometrical parameters of the bearing for two design diagrams with the odd and even number $z$ of the bearing rolling elements. Analytical formulas allow to determine the bearing radial clearance for unloaded condition. In loaded condition of the bearing the radial clearance additionally increases at the expense of the bearing elastic deformations. According to the developed theory with the even number of rolling elements for bearings the radial clearance is larger than for bearings with the odd number of rolling elements. For the first time analytical dependences have been obtained for the determination of the $\varepsilon_1$ value representing the inner ring axis movement with support on two central rolling elements. The obtained analytical dependencies are useful for the further improvement of the structures and operating processes of the rolling bearings.

7. References

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