Analytical studies of radial loads on rolling elements of ball and roller bearings

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Abstract. Rolling bearings have found wide application in mechanical engineering due to their design simplicity and high efficiency during the operation of machinery and equipment [1, 2]. At present the rolling element theory allows to fulfill complex static and dynamic calculations. The problems for the rolling bearing durability calculation, reduction of vibration and noise during the operation of machines and units are of particular relevance. The rolling bearing design simplicity is caused by a small number of component parts. However, dynamic and static processes appearing during the bearing operation possess a complex physical basis and are in need of further study and development. At present the dependence of the radial forces distribution on rolling elements along the bearing rotation angle exists only for the odd diagram of the working rolling element location using the Striebeck method. In the study a new additional design diagram is applied for the even symmetrical location of the bearing working rolling elements in the operating area, which allow to significantly improve the accuracy of performed calculations. The total number of rolling elements in a bearing can be an even or odd number, at the same time the number of working rolling elements taking up a workload in the Striebeck problem is always represented by an odd number. For this reason the known design diagram is of an insufficient accuracy, especially for a small number of rolling elements z. A new procedure of the problem solution relative to the determination of radial loads on rolling elements, where restrictions on the number of rolling elements are eliminated being accepted at present during the bearing calculation.

Key-words: roller bearing, ball bearing, radial load, geometric characteristic of a bearing, number of working rolling elements.

1. Introduction

In work [1] the authors Yerzhan Shayakhmetov, Bolat Manesanov, Zhulduz Dildebaeva, Aigul Shaikhanova, Roman Kochan, Stanislaw Zawislak have developed the algorithm of the belt conveyor bearing load. Maximum loads preceding the bearing seizure moment have been examined. A conclusion has been made regarding the relevance of the study regarding the roller bearing loading aimed at increasing reliability and durability.

In work [2] the authors Xia Yang, Hong Xiao consider the mill roller bearing loading using the finite element method. The load distribution along the roller length and total loading of the roller bearing are examined.

In work [3] the authors Yangang Wei, Xiujuan Zhang, Yan-Kui Liu study the radial load of cylindrical roller bearings. They consider solid and hollow cylindrical roller bearings. The dependence of the
radial stiffness on the load bearing intensity has been established. It has been concluded that hollow rollers reduce contact stresses of bearings.

In their works [4, 5, 6] I.V. Boyarkina, E.V. Tarasov consider a new method of the analytical calculation of loads on rolling elements of the centrifugal pumping unit bearings. In order to improve the calculation accuracy of bearings with a small number of rolling elements \( z < 15 \) in works [7-11] the rolling bearing topical problems are examined.

2. Problem statement
This study considers the solution of a new problem relative to the determination of radial loads on rolling elements for the design diagram were the even symmetrical location of the bearing working rolling elements. The problem solution for the determination of radial loads is connected with the use of the equilibrium equation where the number the equation members represent a variable value which depends on the total number \( z \) of rolling elements – balls or rollers. In order to eliminate this inconvenience in regulatory documents regarding the calculation of rolling bearings a whole range of assumptions is adopted. For ball bearings with the number of rolling elements \( z = 10, \ldots, 20 \) the constant value of the coefficient \( k_1 = 4.37 \pm 0.01 \) is adopted. For roller bearings with the number of rolling elements \( z = 10, \ldots, 20 \) the average value of the coefficient \( k_1 \approx 4.0 \) is adopted [11].

In works [4, 5, 6] the problem relative to the determination of radial loads on rolling elements has been solved for the first time without using the indicated restrictions for the odd and even diagram of the symmetrical location of the working rolling elements – balls and rollers.

The modern technology development, for example, of centrifugal pumping units occurs in the direction of increasing the diameters of rolling elements and reducing the total number \( z \) of rolling elements, for example, for balls this value is adopted as \( z = 6-8 \), for rollers \( z = 10-12 \).

That’s why the need arises to increase the load calculation on rolling elements during the current technology improvement.

The radial load \( P_i \) is unevenly distributed on the rolling elements located in the bearing operating area on the arc of 180°.

The angular pitch \( \gamma \) of the rolling element location in the rolling bearing is determined by the formula

\[
\gamma = \frac{2\pi}{z},
\]

where \( z \) – is the total number of the rolling elements in the bearing.

3. Theory
In the traditional Striebeck diagram (Figure 1,a) the odd number of the rolling elements (balls and rollers) is always present in the operating area.

![Figure 1](image-url)  
**Figure 1.** Location diagrams of rolling elements: a) traditional first odd design diagram; b) second design diagram with even number of rolling elements in operating area.
The equilibrium condition of the concurrent radial force system is determined by the equation of statics

\[ Q = P_0 + 2 \sum_{i=1}^{n_k} P_i \cos \gamma_i , \]

where \( Q \) – is the bearing shaft load; \( P_0 \) – radial load on the central working rolling element; \( P_i \) – radial load on the \( i_{th} \) working rolling element; \( n_k \) – is the number of summands in equation (2).

Figure 1, b shows a new design diagram for the odd number of rolling elements where the number of the working rolling elements is always an even number [4, 5, 6].

The equilibrium of the concurrent force system for Figure 1, b is determined according to the equilibrium equation

\[ Q = 2 \sum_{i=1}^{n_k} P'_i \cos(i - 0.5)\gamma , \]

where \( n_k \) – is the number of summands in equation (3).

For the whole variation range of the total number \( z \) of rolling elements (\( z = 5 \)–36) Table 1 gives values of the bearing working rolling elements for the odd diagram \( z_{p1} \) (Figure 1, a) and for the even diagram \( z_{p2} \) (Figure 1, b). Besides, Table 1 shows the sums of the numbers of working rolling elements for the odd and even diagrams (\( z_{p1} + z_{p2} \)) for all rolling bearings.

**Table 1.** Dependence of the number of working rolling elements for odd and even design diagrams of the total number of rolling elements.

| Total number of bearing rolling elements, \( z \) | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|-----------------------------------------------|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|
| Number of working rolling elements, \( z_p \) | \begin{tabular}{c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c} \hline & \multicolumn{9}{c|}{Odd diagram, \( z_{p1} \)} & \multicolumn{9}{c}{Even diagram, \( z_{p2} \)} \\ \hline & 3 & 3 & 3 & 3 & 5 & 5 & 5 & 5 & 7 & 7 & 7 & 7 & 9 & 9 & 9 \\ \hline \end{tabular} | \begin{tabular}{c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c} \hline & 2 & 2 & 4 & 4 & 4 & 4 & 6 & 6 & 6 & 6 & 8 & 8 & 8 & 8 & 10 \\ \hline \end{tabular} |
| Sum (\( z_{p1} + z_{p2} \)) | \begin{tabular}{c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c} \hline & 5 & 5 & 7 & 7 & 9 & 9 & 9 & 11 & 11 & 13 & 13 & 15 & 15 & 15 & 17 & 17 & 17 \\ \hline \end{tabular} | \begin{tabular}{c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c} \hline & 19 & 21 & 21 & 23 & 23 & 25 & 25 & 27 & 27 & 29 & 29 & 31 & 31 & 33 & 33 & 35 & 35 \\ \hline \end{tabular} |

New regularities and knowledge in the geometry of rolling bearings have been established.

By means of Table 1 it is possible to determine the number of working elements \( z_{p1}, z_{p2} \) for a bearing in the variation range \( z = 5, ..., 36 \), which covers all possible real bearings in technology [5-7, 11].

By means of \( z_{p1} \) for the odd diagram of the working rolling element location (see Figure 1,a), the value \( n_{k1} \) is determined by the formula

\[ n_{k1} = \frac{z_{p1}}{2} - 0.5 , \]

where \( z_{p1} \) – is the number of working rolling elements for the odd diagram.

For the even diagram (see Figure 1,b), the number of summands \( n_{k2} \) in equation (3) is determined by the formula
where \( z_{p2} \) – is the number of working rolling elements for the even diagram.

During the uniform variation of the total number \( z \) of rolling elements, the number of working rolling elements \( z_{p1} \) and \( z_{p2} \) remains unchanged for four consecutive \( z \) values, and then acquires the following odd or even value.

For odd \( z \) values of the total number of rolling elements, the sum of the numbers of working rolling elements for odd and even diagrams is always equal to the total number \( z \) of rolling elements, i.e.

\[
z = z_{p1} + z_{p2}.
\]

For even \( z \) values (see Table 1), the sum of working rolling elements is always less than the total number \( z \) by one, i.e.

\[
z - 1 = z_{p1} + z_{p2}.
\]

The results of Table 1 are presented in a visual graphic form in Figure 2. As per the diagram for any \( z \) value it is possible to determine the number of working elements \( z_{p1} \) and \( z_{p2} \) for two design diagrams (see Figure 1,a,b). The dependence of the sum of the bearing working rolling elements \( (z_{p1} + z_{p2}) \) on the total number \( z \) of the bearing rolling elements is of particular importance.

**Figure 2.** Design diagram for the determination of the number of loaded working rolling elements for the odd diagram \( z_{p1} \) and for the even diagram \( z_{p2} \) of the total number \( z \) of rolling elements.

The dependence of the sum of the bearing working rolling element numbers \( (z_{p1} + z_{p2}) \) on the number \( z \) of the common bearing rolling elements is of a dual character, i.e. it is different for even and odd \( z \) values of the total number of the bearing rolling elements.

The modern theory of rolling bearings doesn’t allow us to answer the question relative to the preference of rolling bearings with an even or odd total number of rolling elements \( z \) in connection with poor accuracy of modern researches and insufficient development of the theory of bearings.

For the odd diagram of the radial force distribution (see Figure 1,a) the Striebeck formula for the determination of the central force \( P_0 \) is known, which has the following form [10]
\[ P_0 = \frac{Q}{k_1}, \] (6)

where \( k_1 \) is a constant integer number of the bearing geometric characteristics. The number \( k_1 \) is determined by the formula for odd diagram [10]

\[ k_1 = 1 + 2 \sum_{i=1}^{n_k} \cos \frac{5}{2} i \gamma, \] (7)

where \( n_k \) is the number of summands in equation (7) and it is determined by formula (4).

After the determination of the force \( P_0 \), the other radial forces are determined by the formula for the odd diagram

\[ P_i = P_0 \cos i \gamma, \quad \text{where} \quad i = 1, \ldots, n_k. \] (8)

Let’s consider the problem solution method relative to the distribution of radial forces for the even design diagram of the ball bearing working rolling element location (see Figure 1, b).

In equilibrium equation (3) for the even design diagram (see Figure 1, b) there is \( 2n_k \) of unknown values for which determination it is necessary to write down the additional equations of the Hertz theory [10] for a ball bearing in the following form

\[ \frac{\lambda_1^3}{p_1^2} - \frac{\lambda_2^3}{p_2^2} = \frac{\lambda_3^3}{p_3^2} - \frac{\lambda_4^3}{p_4^2} = \cdots = \frac{\lambda_{2n_k}^3}{p_{2n_k}^2}, \quad \text{where} \quad i = 1, \ldots, n_k, \] (9)

where \( \lambda_i \) represents the rolling element radial approaching.

In equation (3) the values \( P_i' \) of radial forces can be expressed through the force \( P_0' \) using equation (9). Then, equation (3) of the ball bearing total load (see Figure 1, b) has the following form

\[ Q = 2P_0' \left( \cos 0.5 \gamma + \sum_{i=2}^{n_k} \frac{\cos \frac{5}{2} (i - 0.5) \gamma}{\cos^{3/2} 0.5 \gamma} \right). \] (10)

The constant integer \( k_2 \) for the even diagram of the ball bearing working elements is determined by the formula

\[ k_2 = 2 \left( \cos 0.5 \gamma + \sum_{i=2}^{n_k} \frac{\cos \frac{5}{2} (i - 0.5) \gamma}{\cos^{3/2} 0.5 \gamma} \right). \] (11)

From equation (10) the force \( P_i' \) is determined by the formula

\[ P_i' = \frac{Q}{k_2}. \] (12)

Other forces are determined as follows

\[ P_i' = P_0' \cos (i - 0.5) \gamma, \quad \text{where} \quad i = 2, \ldots, n_k. \] (13)

For roller bearings the design diagrams relative to the rolling element radial force determination have different forms for the odd (see Figure 1, a) and even (see Figure 1, b) design diagrams.

Regarding the odd diagram of the working rolling element location (see Figure 1, a) Striebeck formulas for roller bearings are known. The coefficient \( k_1 \) for the odd diagram of the roller bearing is determined by the formula

\[ k_1 = 1 + 2 \sum_{i=1}^{n_k} \cos 2 i \gamma. \] (14)

The radial force \( P_0 \) for the middle roller (see Figure 1, a) is determined by the formula...
\[ P_0 = \frac{Q}{k_1}. \]  

(15)

Other radial forces for roller bearing are determined by the formula

\[ P_i = P_0 \cdot \cos \gamma, \quad \text{where} \quad i = 1, \ldots, n_k. \]  

(16)

Let’s consider in more details the radial load calculation method on the roller bearing rolling elements for the new diagram of the roller location (see Figure 1,b).

The equilibrium equation of the roller bearing concurrent force system (see Figure 1,b) has the following form (3)

\[ Q = \sum_{i=1}^{n_k} 2P_i \cos(i - 0.5)\gamma. \]  

The equations of the radial deformations of the rolling elements approaches \( \lambda_i \) with the inner ring for the second design diagram of the roller bearing (see Figure 1,b) are written down as follows

\[ \lambda_i = \lambda_0 \cdot \cos(i - 0.5)\gamma, \quad \text{where} \quad i = 1, \ldots, n_k. \]  

(17)

The equation of connections of the radial approaches \( \lambda_i \) proportional to the radial loads \( P_i \) according to the Hertz theory for roller bearings has the following form

\[ \frac{\lambda_1}{P_1} = \frac{\lambda_2}{P_2} = \frac{\lambda_3}{P_3} = \frac{\lambda_4}{P_4} = \frac{\lambda_5}{P_5} = \cdots = \frac{\lambda_2}{P_2}, \quad \text{where} \quad i = 1, \ldots, n_k. \]  

(18)

Equations (17), (18) allow to express the radial forces \( P_i \) through the radial force \( P_1' \) for the even location of rolling elements

\[ P_i' = P_1' \cdot \frac{\cos(i - 0.5)\gamma}{\cos 0.5\gamma}, \quad \text{where} \quad i = 2, \ldots, n_k. \]  

(19)

Using equation (19) let’s represent expression (3) for the even number of working elements in the following form

\[ Q = 2P_1' \left( \cos 0.5\gamma + \sum_{i=2}^{n_k} \frac{\cos(i - 0.5)\gamma}{\cos 0.5\gamma} \right). \]  

(20)

From equation (20) we determine for the roller bearing for the even number of elements

\[ P_1' = \frac{Q}{k_2}, \]  

(21)

where \( k_2 \) – is the roller bearing constant value for the second even design diagram (see Figure 1,b) is determined by the formula

\[ k_2 = 2 \left( \cos 0.5\gamma + \sum_{i=2}^{n_k} \frac{\cos(i - 0.5)\gamma}{\cos 0.5\gamma} \right). \]  

(22)

After the calculation of the force \( P_1' \) according to expression (21) we determine other radial forces by formula (19).

4. Results discussion

For the improvement of the calculation reliability relative to the proposed procedure, Table 2 has been obtained with the geometric characteristic coefficient values for the odd diagram of working rolling elements \( k_1 \) and for the even diagram of working rolling element location \( k_2 \) for all \( z \) values of the total number of rolling elements of ball bearings and roller bearings.

We’ll consider the application of the developed procedure for rolling bearings of centrifugal pumping units [10].
In centrifugal pumping units with electric motor of the power \( N_{el, motor} = 560 \text{ kW} \) ball bearings 46416 are used. The bearing has the following parameters: inner diameter \( d = 80 \text{ mm} \), outer diameter \( D = 200 \text{ mm} \), rolling element diameter \( D_w = 38.1 \text{ mm} \), total number of rolling elements \( z = 7 \), static load capacity of bearing \( C_0 = 125 \text{ kN} \).

For the problem solution we take the total load \( Q \) of the bearing equal to the static load capacity \( Q = C_0 = 125 \text{ kN} \), limit rotation frequency of rotation \( n_{\text{limit}} = 3000 \text{ rpm} \).

According to Figure 2 for the bearing with \( z = 7 \) we determine the number of working rolling elements for the odd diagram \( z_p_1 = 3 \), for the even diagram \( z_p_2 = 4 \).

According to Table 2 we determine the geometric coefficient \( k_1 \) for the odd diagram \( z = 7 \) of the ball bearing working elements

| Number of rolling elements \( z \) | \( k_1 \) Ball bearings | \( k_2 \) | \( k_1 \) Roller bearing | \( k_2 \) |
|---|---|---|---|---|
| 5 | 1.10616613 | 1.61803400 | 1.19098303 | 1.61803400 |
| 6 | 1.35355342 | 1.73205082 | 1.50000003 | 1.73205082 |
| 7 | 1.61390815 | 1.85656289 | 1.77747910 | 1.91185403 |
| 8 | 1.84089644 | 2.05179478 | 2.23395560 | 2.41147416 |
| 9 | 2.05235421 | 2.26714444 | 2.50000003 | 2.62865559 |
| 10 | 2.28356636 | 2.47328548 | 2.85656289 | 3.10582859 |
| 11 | 2.52066848 | 2.67372654 | 3.11709884 | 3.35497138 |
| 12 | 2.74946072 | 2.88943043 | 3.35497138 | 3.61803400 |
| 13 | 2.97205145 | 3.11709884 | 3.61803400 | 3.87558521 |
| 14 | 3.20162972 | 3.33424444 | 3.87558521 | 4.12717050 |
| 15 | 3.43401339 | 3.54614110 | 4.12717050 | 4.3786737 |
| 16 | 3.66293239 | 3.76930390 | 4.42566691 | 4.6791983 |
| 17 | 3.88871007 | 4.02774606 | 4.6791983 | 5.00000003 |
| 18 | 4.11787128 | 4.21585882 | 4.95000003 | 5.35900908 |
| 19 | 4.34860309 | 4.43716735 | 5.35900908 | 5.701571705 |
| 20 | 4.57751524 | 4.66159165 | 5.701571705 | 6.05232571 |
| 21 | 4.80458800 | 4.88772196 | 6.05232571 | 6.40817771 |
| 22 | 5.03359440 | 5.11282918 | 6.40817771 | 6.79423841 |
| 23 | 5.26358006 | 5.33679475 | 6.79423841 | 7.17810127 |
| 24 | 5.49247401 | 5.56260301 | 7.17810127 | 7.60167771 |
| 25 | 5.72018407 | 5.78947631 | 7.60167771 | 8.054429316 |
| 26 | 5.94911951 | 6.01569131 | 8.054429316 | 8.5170203 |
| 27 | 6.17871291 | 6.24112380 | 8.5170203 | 9.00000003 |
| 28 | 6.40759156 | 6.46775044 | 9.00000003 | 9.471571705 |
| 29 | 6.63566514 | 6.69509372 | 9.471571705 | 10.03232571 |
| 30 | 6.86455431 | 6.92198327 | 10.03232571 | 10.5170203 |
| 31 | 7.09391928 | 7.14056944 | 10.5170203 | 11.00000003 |
| 32 | 7.32278656 | 7.37546077 | 11.00000003 | 11.5170203 |
| 33 | 7.55106601 | 7.60312107 | 11.5170203 | 12.03232571 |
| 34 | 7.77994261 | 7.83045261 | 12.03232571 | 12.5170203 |
| 35 | 8.00916440 | 8.05736286 | 12.5170203 | 13.00000003 |
| 36 | 8.23802336 | 8.28487081 | 13.00000003 | 13.5170203 |

5. Consideration of the results

The radial force \( P_0 \) on the central element for the odd diagram (see Figure 1,a) is determined by the formula \( P_0 = Q/k_1 = 77.4517 \text{ kN} \), angular pitch of the rolling element location is equal to \( \gamma = \frac{2\pi}{z} = 51.4285^\circ \), number of summands in formula (4) is equal to \( n_k = 1 \).
The radial lateral forces $P_1$ of the odd diagram bearing are determined by the formula $P_1=P_0\cos\gamma=48.2903$ kN.

It is clear from the example that the traditional calculation method for a small number of odd rolling elements allows to obtain only three values of radial forces: $P_0=77.4517$ kN and two radial forces $P_1=48.2903$ kN.

The even diagram of the working rolling element location (see Figure 1,b) allows to obtain additional values of the radial forces $P'_i$ for other angles of the rolling element location.

For the even diagram with $z=7$ the number of working elements $z_{p2}=4$ (see Figure 2). Consequently, the number of summands in the equilibrium equation is equal to $n_k=2$, coefficient $k_2=1.85656289$ (see Table 2).

The radial force $P'_1$ for the even ball bearing diagram is determined by the formula $P'_1=\frac{Q}{k_2}=67.3287$ kN. Other radial forces are determined by formula (19) $P'_i=P'_1\frac{\cos(i-0.5)\gamma}{\cos 0.5\gamma}=16.48$ kN.

Figure 3 by means of on graph schematically shows the distribution of radial forces for rolling elements for odd and even design diagrams, that allows to obtain a sufficient number of points of the general dependence of the bearing radial forces with a small number of rolling elements $z_{p1}$ and $z_{p2}$.

![Figure 3](image_url)

**Figure 3.** Radial forces in ball bearing 46416 for the number of working elements $z_{p1}=3$ for the odd diagram and $z_{p2}=4$ for the even diagram.

In Figure 3 the radial force distribution curve characterizes the loading process of each rolling element in one revolution of the bearing shaft. The rotation angle $\varphi$ equal to $180^\circ$ is proportional to specific operating time of each rolling element in one revolution of the bearing.

6. Conclusion

The design diagram has been developed for the even location of rolling elements in the operating area, which in combination with the known odd diagram provides a new more complete solution of the problem relative to the distribution of radial forces in rolling bearings. New analytical formulas have been obtained regarding the distribution of forces in the bearing rolling elements for the even design diagram. Tables have been obtained increasing the load calculation reliability in the bearing rolling elements in the construction and general engineering.
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