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A METHOD OF PRELOAD SELECTION FOR A SYSTEM OF ANGULAR CONTACT BALL BEARINGS DUE TO THE MOMENT OF FRICTION

METODA DOBORU NAPIĘCIA WSTĘPNEGO UKŁADU ŁOŻYSK KULKOWYCH SKOŚNYCH ZE WZGLĘDU NA MOMENT TARCIA

Key words: angular contact ball bearings, bearing arrangement, preload, basic rating life, method of preload selection, system of angular contact, moment of friction.

Abstract Angular contact ball bearings are usually used in the situation when high stiffness of a bearing is demanded. However, a significant stiffness improvement can be achieved only after introducing a preload ("assembly clamp") into a system of angular bearings. The aim of the research was to develop a method of preload selection for a system of angular contact ball bearings. As a result, a higher stiffness of the bearing without significant loss in its durability will be obtained.

Słowa kluczowe: łożyska kulkowe skośne, układ łożysk, napięcie wstępne, trwałość znamionowa, sposób doboru napięcia wstępnego, układ styku kątowego, moment tarcia.

Streszczenie Łożyska kulkowe skośne są zwykle stosowane w sytuacjach, kiedy potrzebne jest uzyskanie dużej sztywności łożyskowania. Jednakże znaczące zwiększenie sztywności można uzyskać dopiero dzięki wprowadzeniu napięcia wstępnego (tzw. zacisku montażowego) do układu łożysk skośnych. Celem przedstawionej pracy było opracowanie takiej metody doboru napięcia wstępnego układu łożysk kulkowych skośnych, wskutek której byłoby osiągnięte zwiększenie sztywności łożyskowania bez znaczącego uszczerbku dla jego trwałości.

INTRODUCTION

The benefit from such a significant advantage of angular contact ball bearings is the increase of the bearing stiffness, which is possible at its fullest only with the use of a preload. By general understanding, a preload has a disadvantage of loading rolling elements, which must lead to a decrease in the durability of a bearing compared to the situation before the preload introduction. However, diagnostics research performed by the author has shown that it is possible to find such a value of preload for which a decrease rather than an increase of the average load of rolling elements in one of the bearings in the system can be observed, while the loads increase very insignificantly in the second bearing.

Regulation of preload of angular bearings is mentioned in the literature on the subject, but only as a practical action based on experience, but without a selection method. At present, there exists no widely accepted method of preload selection. Neither the literature on subject nor the catalogues of bearings published by their producers give indications concerning the selection of the parameter; therefore, it is most frequently selected intuitively. Still, it is known that its incorrect selection may have a catastrophic effect on the durability of bearings. Thus, there exists a problem of the accurate selection of preload (i.e. of the one that will not cause a significant loss in bearings durability).

According to the literature on subject **[L. 1, 2, 8]**, and **[L. 12]**, the main objectives behind the use of preload are the following: an increase of the stiffness of a system of bearings, a reduction of noise during work, an increase of the accuracy of shaft run, a compensation of processes of wearing out and settling during work, and an assurance of a longer lifetime.

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A preload can be expressed as a force or as a dislocation (distance), although the force of preload is the basic parameter of the specification **[L. 12]**. Depending on the regulation method, a preload is indirectly associated with the moment of friction in the bearing .

Optimum values of preload can be achieved on the basis of proven constructions, which are then applied in similar constructions **[L. 1**, **12]**. In case of new constructions, it is recommended to calculate the force of preload and check the correctness of calculations by means of experimenting. In practice, it may be necessary to introduce corrections, because not all real work parameters can be accurately known. The reliability of calculations depends primarily on the extent to which the assumptions are made in relation to temperature conditions during work and the elastic deformations of cooperating elements (predominantly of a mounting) are accordant with real conditions.

According to **[L. 12],** while determining the preload, the first task is to calculate the target force of preload, assuring an optimum combination of stiffness, exploitation time, and the reliability of the work of a bearing. Then, the next task is to calculate the force of preload to be used while setting the bearings during assembling. During work, the bearings should have the temperature of the surroundings and cannot be a subject to a working load.

CALCULATION METHOD

As mentioned in **[L. 5],** in order to solve the problem, it is necessary to associate a number of interdependent questions. The most significant out of these questions is to determine elastic displacements in the bearing. Displacements in bearings cause reactions in bearing systems.

A method of determining displacements in a bearing has been presented in the papers **[L. 3–7, 9, 10]**.

The problem solving required is associated with the following problems:

1) The deflection line of machine shaft for a complex external load,
2) The dislocations of inner rings in bearings in relation to the outer ones as a result of loads plus preload,
3) The influence of heat deformations of the shaft and fitting on dislocations,
4) Dislocations in the contact of rolling parts and deformation in the contact between the rolling parts and the raceways of both bearings of the system,
5) Calculating contact forces in bearings on the basis of contact deformations,
6) A balance between inner (contact) forces in bearings and the external load of the whole bearing, and
7) Calculating durability of bearings basing on contact forces.

CALCULATIONS

For a representative analysis, the author selected a system of two angular ball bearings compatible with the model presented in the first part of the article **[L. 5]**, with 7212B bearings and parameters as given in **Table 2.** The dynamic load capacity of the bearings C was determined according to **[L. 11]**.

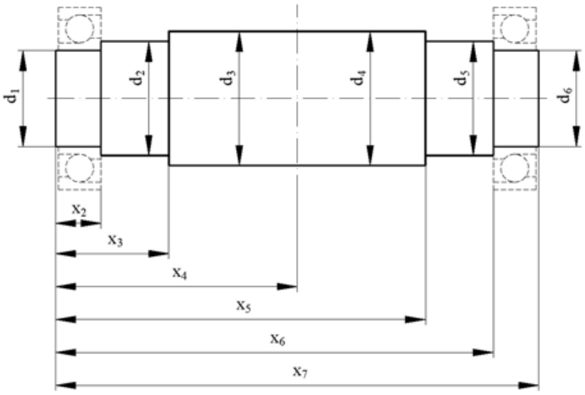

Fig. 1. A draft of a model shaft [L. 5]
Rys. 1. Szkic modelowego wału **[L. 5]**

Table 1. Dimensional parameters of model shaft [mm] [L. 5]
Tabela 1. Parametry wymiarowe modelowego wału [mm] **[L. 5]**

Parameter	Parameter dimension
x_2	22
x_3	100
x_4	200
x_5	300
x_6	378
x_7	400
d_1	60
d_2	67
d_3	75
d_4	75
d_5	67
d_6	60

A coordinate of the beginning of the shaft x_1 equal to zero was assumed for all model shafts.

Table 2. Reduce the increase of the moment of working surfaces of bearings – assumed for calculations
Tabela 2. Wymiary powierzchni roboczych łożysk przyjętych do obliczeń

Bearing →	7212B
Ball diameter D_b [mm]	15.875
Diameter of the inner ring raceway d_{ir} [mm]	68.976
Diameter of the outer ring raceway d_{or} [mm]	101.059
Transverse radius of the inner ring raceway r_{ir} [mm]	8.180
Transverse radius of the outer ring raceway r_{or} [mm]	8.330
Number of rolling elements Z	15
Bearing load capacity C [N]	57200

Shaft loads are associated with limiting force F_{c1}, being 0.075 C, 0.1 C, and 0.125 C. Values of the remaining forces are accordingly: $F_{c1} = F_{c2}$, $F_{p1} = F_{p2}$, $F_{x1} = F_{x2}$, and radial force F_p equals 0.364 of limiting force, assuming that the angle of engagement for a gear wheel is approximately 20º, and the axial force F_x has the following values: 0, $0.049{\cdot}F_c$, $0.098{\cdot}F_c$, $0.196{\cdot}F_c$, and $0{,}92{\cdot}F_c$. These forces are designated in relation to the limiting force.

The locations of load surfaces have been assumed in relation to the length of shaft L_w, equal to the dimension $x_7 = 400$mm and are as follows (**Fig. 2**):

- For Variation I of the load: $x_L = 0.3{\cdot}L_w$, $x_L = 0.4{\cdot}L_w$, $x_L = 0.5{\cdot}L_w$ $x_L = 0.6{\cdot}L_w$, $x_L = 0.7{\cdot}L_w$
- For Variation II of the load: $x_{L1}= 0.4{\cdot}L_w$ and $x_{L2}= 0.6{\cdot}L_w$.

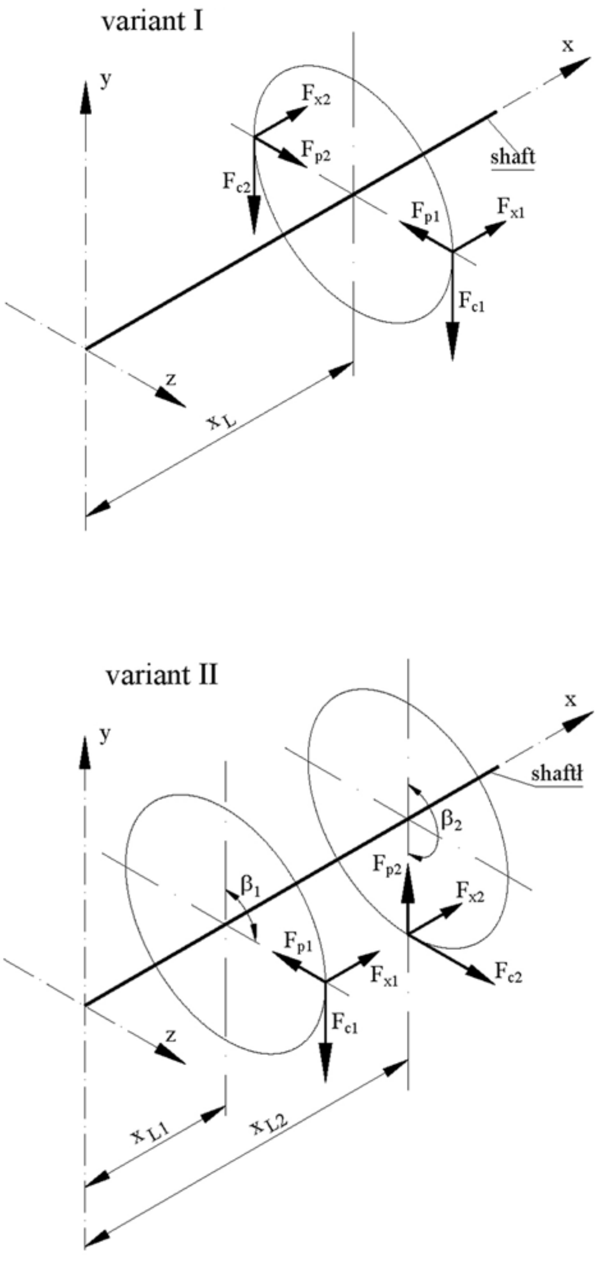

Fig. 2. The assumed variations of bearing loads
Rys. 2. Przyjęte warianty obciążeń łożyskowania

In the first step to solving the problem W_M indicator was determined and denoted as the friction torque indicator. The friction torque indicator expresses the friction moment of a bearing depending on the applied preload. How the indicator is determines has been presented in detail in **[L. 7]**.

In order to determine acceptable preload values, on the emergent characteristics of W_M indicator, such values of preload Z_c were read with which characteristics increased by 10%, and out of these, the graphs of Z_c values were created **(Fig. 3) [L. 7]**.

They were treated as acceptable values of preload, because a further increase will cause a beneficial increase of the rigidity of the bearing at the cost of a significant increase of the moment of friction.

The following graphs present acceptable values of preload obtained for various locations of the shaft load.

On the basis of obtained characteristics, the author selected the ones corresponding to the relative transverse load of the bearing $F_c/C = 0.1$, which are presented in **Fig. 4.**

It turns out that the location of load plane influences the acceptable preload, but this dependence is not unequivocal. Moreover, it is not possible to test all configurations of load locations. Thus, it was decided that, for the purpose of practical recommendations, such values of limiting preload will be given that will prove appropriate for a possibly wide range of load positionss. Such values result from the lower boundary of characteristics presented in **Fig. 3.** Due to practical reasons, Z_c was replaced by Z_o in the lower limit.

Taking the results into consideration (**Fig. 3** and **Fig. 4**), two alternative procedures were developed for determining the recommended preload for ball bearings due to friction moment.

A) Procedure based on dependence of the acceptable preload on relative axial load

The basic dependence is assigned by the line Z_o obtained in **Fig. 4.** It corresponds to the relative transverse load of the bearing $F_c = 0.1$ C.

The dependence of the acceptable Z_c value on the relative transversal load has been based on the graphs in **Fig. 3**. For this purpose, in each of the graphs, quotients of Z_c were read with relative load $F_c/C = 0.075$ and with relative load $F_c/C=0.1$ at three points, and then (also at three points) quotients of the Z_c value with the relative load of $F_c/C=0.125$ and with the relative load of $F_c/C = 0.1$. Thus, the determined quotients are collected in **Tables 3** and **4.**

Scattering of quotients collected in the above tables are illustrated in **Fig. 5** with the use of (it is not possible to present all points due to their proximity or overlapping). After that, the points collected in **Tables 3** and **4** with the last squares method were approximated. The obtained straight line is also presented in **Fig. 5.**

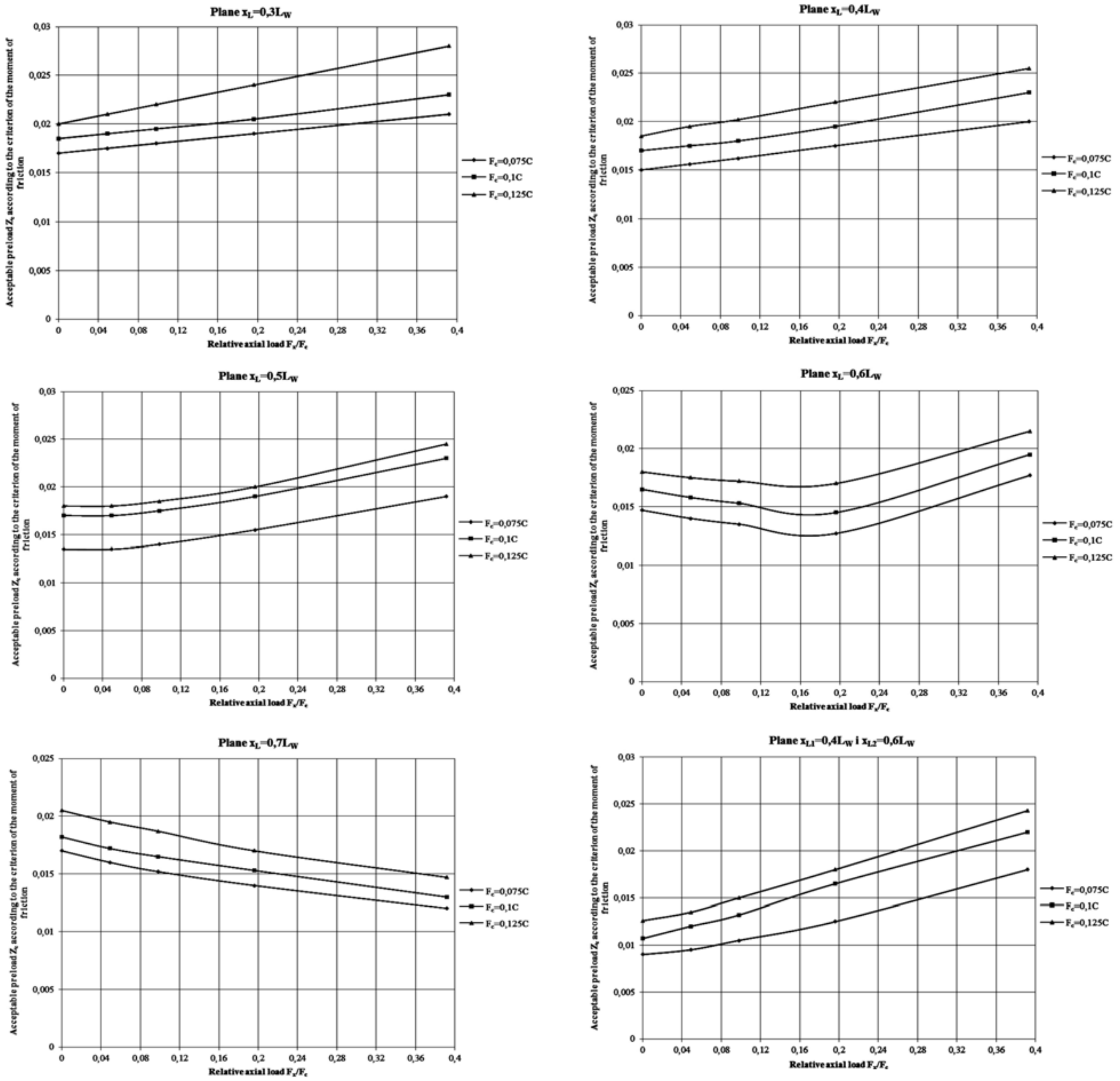

Fig. 3. Acceptable preload Z_c according to the criterion of the moment of friction in the function of relative axial load F_x/F_c

Rys. 3. Dopuszczalny zacisk wstępny Z_c wg kryterium momentu tarcia w funkcji względnego obciążenia osiowego F_x/F_c

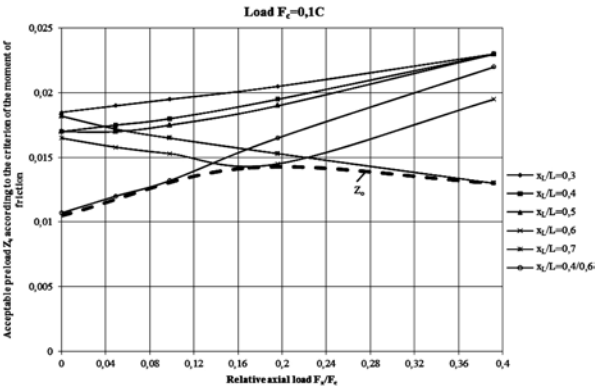

Fig. 4. Dependence of the boundary preload Zc on the axial load at different load positions

Rys. 4. Zależność granicznego zacisku wstępnego Z_c od obciążenia osiowego przy różnych położeniach obciążeń

Table 3. Values of quotients of acceptable Z_c for $F_c/C = 0.075$ and $F_c/C = 0.1$
Tabela 3. Wartości ilorazów dopuszczalnego Z_c dla $F_c/C = 0,075$ i $F_c/C = 0,1$

Load plane	Values of quotients		
$x_L = 0.3 \cdot L_w$	0.919	0.927	0.923
$x_L = 0.4 \cdot L_w$	0.885	0.896	0.872
$x_L = 0.5 \cdot L_w$	0.797	0.820	0.830
$x_L = 0.6 \cdot L_w$	0.891	0.877	0.907
$x_L = 0.7 \cdot L_w$	0.934	0.915	0.924
$x_{L1} = 0.4 \cdot L_w$ and $x_{L2} = 0.6 \cdot L_w$	0.840	0.766	0.824

Table 4. Values of quotients of acceptable Z_c for $F_c/C = 0.125$ and $F_c/C = 0.1$
Tabela 4. Wartości ilorazów dopuszczalnego Z_c dla $F_c/C = 0,125$ i $F_c/C=0,1$

Load plane	Values of quotients		
$x_L = 0.3 \cdot L_w$	1.080	1.160	1.210
$x_L = 0.4 \cdot L_w$	1.090	1.130	1.110
$x_L = 0.5 \cdot L_w$	1.060	1.057	1.066
$x_L = 0.6 \cdot L_w$	1.090	1.170	1.110
$x_L = 0.7 \cdot L_w$	1.120	1.110	1.132
$x_{L1} = 0.4 \cdot L_w$ and $x_{L2} = 0.6 \cdot L_w$	1.168	1.090	1.100

The obtained approximation line can be expressed with the the following relation:

$$\frac{Z_c}{Z_{c\,0.1}} = 3\left(\frac{F_c}{C}\right)^{0.477}$$

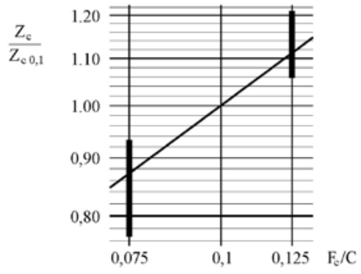

Fig. 5. Dependence of Z_c acceptable due to the moment of friction on transverse load
Rys. 5. Zależność Z_c dopuszczalnego ze względu na moment tarcia od obciążenia poprzecznego

When applied to any freely loaded systems of bearings, F_c should be treated as the geometrical sum of transversal forces and C as the sum of dynamic load capacities. In this way, the correction factor of transverse load k_p was obtained:

$$k_p = 3\left(\frac{\Sigma F_c}{\Sigma C}\right)^{0.477} \qquad (1)$$

where ΣF_c – the resultant transverse forces operating on the wheels hanged on the shaft,
ΣC – sum of dynamic load capacity of both the bearings.

When looking for the acceptable value of preload for the bearing system based on two bearings 7212B due to the moment of friction, one should read the value Z_o from Graph 4 using the relative value of axial forces, and one should then multiply the obtained number by factor k_p (according to Formula 1) dependant on relative transverse load in the bearing.

The results of the research for the 7212B bearing were transferred onto other angular contact ball bearings by the rules of similarity and proportionality of characteristics. In order to test the degree of proportionality, graphs of acceptable preload were made by the criterion of 10% of the moment of friction for the remaining types of angular contact bearings with the load located half-length of the shaft for Variation I and for Variation II of the load. In order to draw these graphs, W_M curves were developed and used for other dimensions of bearings, which enabled determining the characteristics of acceptable values of preload Z_c for the remaining types of angular contact ball bearings.

By comparing the obtained characteristics of the acceptable value of preload Z_c, The following can be concluded:

- There exists a similarity between the course of the line $Z_c = f(F_x/F_c)$.
- There exists a probability of configurations of lines corresponding to various levels of relative transverse load F_c/C.

In order to determine the degree of proportionality between characteristics for different types of angular contact bearings, **Figures 6** and **7** were developed.

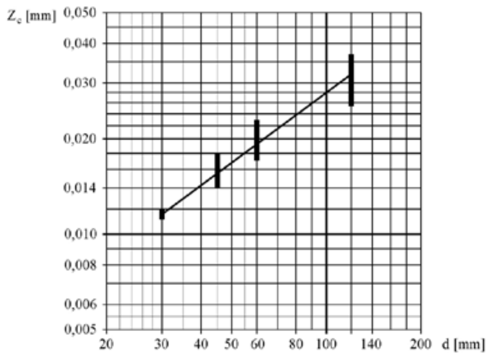

Fig. 6. Dependence of acceptable preload on the diameter of the bearing for Variation I of the load, averaged for different levels of the load according to the criterion of the moment of friction
Rys. 6. Zależność dopuszczalnego zacisku wstępnego od średnicy łożyska przy I wariancie obciążenia, uśredniona dla różnych poziomów obciążenia, wg kryterium momentu tarcia

Figure 6 presents a graph representing calculations according to Variation I of the load, and **Figure 7** presents the same according to Variation II.

The above graphs were developed in the following way: By using the obtained characteristics of acceptable values of preload Z_c, first the ranges of Z_c values were read, within which the lines corresponding to the ranges of the average load ($F_c/C = 0.1$). These ranges are marked in **Figs. 6** and **7** as thick, vertical bands determined for the diameters of the bearing opening d = 30, 45, 60, and 120 mm. After that, on the first and second figure, lines were developed that approximate the scattered results to a straight line with the use of the least squares method. The author concluded that the straight line in **Figure 6** determines the proportionality with a correlation coefficient of 0.72, and in the **Fig. 7**, with a correlation coefficient of 0.68. Finally it was assumed that the preload acceptable due to the moment of friction is proportional to the diameter of the bearing with a correlation coefficient of 0.7.

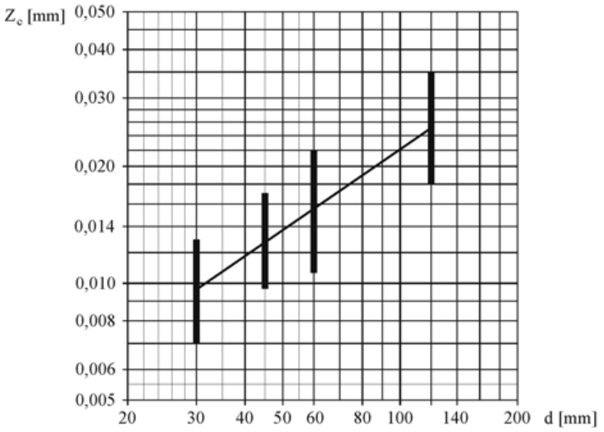

Fig. 7. The dependence of the acceptable preload on the diameter of the bearing for Variation II of the load, averaged for varied levels of load, according to the criterion of the moment of friction

Rys. 7. Zależność dopuszczalnego zacisku wstępnego od średnicy łożyska przy II wariancie obciążenia, uśredniona dla różnych poziomów obciążenia, wg kryterium momentu tarcia

The conclusion is that, when having the value Z" = Z_c determined from **Fig. 4** for the diameter of 60 mm, the value of Z_c can be calculated for a different diameter with the use of correction factor in the following form:

$$k_d = \left(\frac{d}{60}\right)^{0.7} \tag{2}$$

The determination of preload acceptable due to the moment of friction as presented above is based on the assumption that a 10% increase of this moment is accepted. An appliance user (e.g., of a machine or vehicle) may of course reduce the increase of the moment of friction more significantly. Based on the calculations performed, the presented method can be adjusted to a stricter limit. It has been observed that the characteristics of W_M index in the range of minor growths (actually up to around 10%) run along almost straight lines. In consequence, it is possible to introduce a simple factor correcting the accessible preload on the basis of a value of an acceptable moment of friction different than 10%. The factor has the following form:

$$k_M = 0.1 \cdot \delta_M \tag{3}$$

where δ_M is an acceptable increase of the moment of friction due to application of preload, expressed in percentage, with a restriction that δ_M does not exceed 10%.

Thus, it is possible to specify the method of determining the acceptable preload by the criterion of the limited moment of friction.

From **Fig. 4**, the value Z_o has to be determined based on the relative value of axial forces. Then, the value must be corrected with the following:

1) Factor k_p dependant on the relative transverse load of the bearing,
2) Factor k_d dependant on the diameter of the bearing, and
3) Factor k_M dependant on the acceptable increase of the moment of friction.

The method can be included in the following formula:

$$Z_{c.dop.M} = Z_o \cdot k_p \cdot k_d \cdot k_M \tag{4}$$

where symbol $Z_{c.dop.M}$ stands for the preload acceptable due to the assumed limitation of the moment of friction, taking into consideration the size and the loading of the system of angular ball bearings.

B) Procedure based on the dependence of the acceptable preload on the diameter of the bearing

It can be concluded from **Fig. 4** that preload is most limited in the case of Variation II of the load. Thus, the author used the graphs obtained for this variation in relations to the 7212B bearing. Based on the initial points (for $F_x = 0$) of the characteristics for the relative transverse load (F_x/C) = 0.1, a graph presented in **Fig. 8** was developed.

This graph, developed in the function of the inner diameter of the bearing, was assumed to be the basis of the procedure.

In order to condition the selection of preload on the transverse load, correction factor k_p, previously obtained and illustrated in **Fig. 5**, was used (Equation 1).

In order to condition the selection of preload on the axial load, the line Z_o from the graph visible in **Fig. 4** was used. The course of the line is presented again in a relative approach in **Fig. 9**. In this way, the correction factor k_o was obtained

The method described above must enable taking into consideration the increase of an acceptable moment of friction different from 10%. The same k_M factor will be used for that purpose as the one used in the previous procedure.

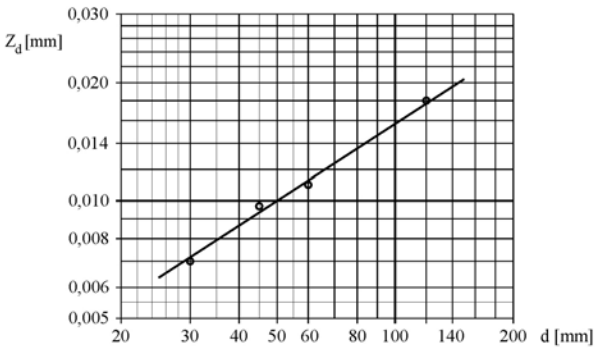

Fig. 8. Dependence of the acceptable preload on the diameter of the bearing for Variation II of the load, for transverse load (F_x/C) = 0.1, with the zero axial force according to the criterion of the moment of friction

Rys. 8. Zależność dopuszczalnego zacisku wstępnego od średnicy łożyska przy II wariancie obciążenia, przy obciążeniu poprzecznym (F_x/C) = 0,1, przy zerowej sile osiowej, wg kryterium momentu tarcia

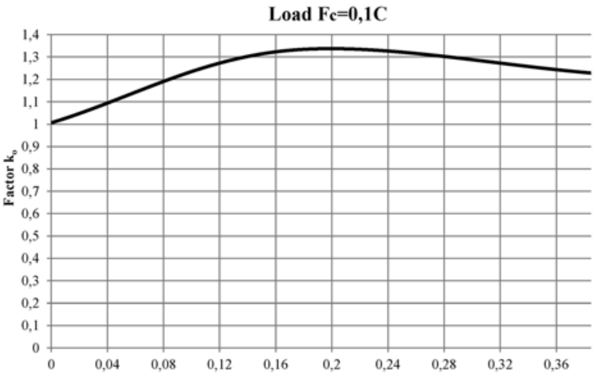

Fig. 9. Dependence of the acceptable preload on the relationship between the axial force and the transverse load (axial load factor), according to the criterion of the moment of friction

Rys. 9. Zależność dopuszczalnego zacisku wstępnego od stosunku siły osiowej do obciążenia poprzecznego (współczynnik obciążenia osiowego), wg kryterium momentu tarcia

Thus it is possible to specify the method of determining the acceptable preload according to the criterion of limited moment of friction.

In **Fig. 8**, the value Z_d has to be determined on the basis of the diameter of the bearing and then corrected as follows:

1) Factor k_p dependant on the relative transverse load of the bearing (Equation 1),
2) Factor k_o dependant on the relative axial load of the bearing (graph in **Fig. 9**),
3) Factor k_M dependant on the acceptable increase of the moment of friction (Equation 3).

The method can be included in the following equation:

$$Z_{c.dop.M} = Z_d \cdot k_p \cdot k_o \cdot k_M \tag{5}$$

where symbol $Z_{c.dop.M}$ stands for preload acceptable due to the assumed limitation of the moment of friction taking into consideration the size and the load of a system of angular ball bearings.

CONCLUSIONS

The paper presents two methods of preload selection in the system of angular ball bearings based on the criterion of the moment of friction. The first presented procedure is less convenient, because the starting point is the load parameter (F_x/F_c), which difficult to determine or even variable. The second procedure seems to be more convenient, because its starting point (the diameter of bearings) is an objective parameter.

In general, the preload in the system of angular ball bearings should be determined taking into consideration the following indications:

1. In the aspect of the stiffness of the bearing, the stronger the preload, the better.
2. In the aspect of durability of bearings, the value of preload must be limited. Only in some cases is it possible to achieve the increase of the durability of both bearings for a specific value of preload. In general, a minor drop in the durability of a less loaded bearing has to be accepted. When a shaft is supported on two identical bearings, the decrease of durability is not harmful for a total durability of the bearings.
3. In the aspect of the moment of friction of the bearing, the higher the preload, the worse.

As one can see, it is indispensable to determine the acceptable preload according to two criteria independent from each other. In the course of the presented analyses, two independent methods of determining the acceptable value for a system of two identical ball bearings were developed: (1) according to the criterion of durability **[L. 6]** and (2) according to the criterion of the moment of friction **[L. 7]**, which was illustrated in this study.

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