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INFLUENCE OF LUBRICANT CONTAMINATION ON BALL BEARING RATING LIFE
UTICAJ KONTAMINACIJE MAZIVA NA RADNI VEK KUGLIČNOG LEŽAJA

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Ključne reči
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Abstract

This paper examines the service life of deep groove ball bearings, emphasizing a systems approach to service life calculation according to ISO 281. The contamination in the lubricant can accelerate wear and fatigue on the contact surfaces of bearings, leading to shortened service life. The paper investigates the influence of lubricant contamination on the service life of bearings using empirical data and established standard formulas. The resulting diagrams analytically show how service life varies depending on bearing size and operating conditions, such as lubricant viscosity, sealing efficiency, and load levels. The study's findings offer a more accurate understanding of ball bearing service life estimation under real operating conditions.

Izvod

Ovaj rad se bavi istraživanjem radnog veka kugličnih kotrljajnih ležaja sa radijalnim dodirom, naglašavajući sistemski pristup proračunu radnog veka saglasno ISO 281. Kontaminacija u mazivu može ubrzati habanje i zamor na kontaktnim površinama delova ležaja, što dovodi do skraćenja radnog veka. U radu se istražuje uticaj kontaminacije mazivom na nominalni radni vek kotrljajnog ležaja, primenom empirijskih podataka i ustanovljenih standardnih izraza. Dobijeni dijagrami analitički pokazuju kako radni vek varira u zavisnosti od veličine ležaja i radnih uslova, kao što su viskozitet maziva, efikasnost zaptivanja i intenzitet opterećenja. Rezultati nude preciznije razumevanje procene radnog veka kugličnih kotrljajnih ležaja u stvarnim radnim uslovima.

INTRODUCTION

The calculation of the rating life of rolling bearings follows established standards. This is crucial for their design, production, distribution, and use /1/. The service life of a rolling bearing is the number of load cycles (number of revolutions) or the operating time of the bearing until failure. The failure of a rolling bearing is the loss of its operational ability due to the damage of one or more bearing parts - rings, rolling elements, or cage. In most cases, failure of rolling bearings occurs due to material fatigue and inadequate lubrication, /2/. Failure also occurs due to contamination of the lubricant (poor sealing or poor lubricant filtration, if provided).

When a designer selects a rolling bearing for a particular application, he needs to determine the number of revolutions or the time the bearing will operate without failure with the desired reliability. For this purpose, a standardised formula for the rating life of rolling bearings is used /1, 3/, for which it is necessary to have characteristics of the bearing and to know the parameters of the operating conditions. If the correct bearing that has been correctly transported and stored, is correctly installed, correctly exploited (with designed rotation speed and load of certain direction and intensity) and correctly maintained (regularly lubricated with the appropriate type and amount of lubricant, and effectively protects against the penetration of particle debris and moisture), then the main cause of bearing parts damage is fatigue.

According to ISO standard on damage and failure of rolling bearings /4/, damage due to fatigue can be both subsurface- and surface initiated. The calculation of the standard basic rating life of the bearing is based on the assumption of subsurface-initiated fatigue. However, the standard for the calculation of dynamic load rating and rating life of rolling bearings /3/ also takes into account the influence of surface-initiated fatigue on the service life of the bearing by applying the appropriate factor which modifies the expression for the basic rating life. This modification factor depends on the characteristics of lubrication, the state of the environment (contamination) and the characteristics of the material - the fatigue load limit of the rolling elements material and raceways, /3, 5/.

This paper aims to investigate the influence of lubricant contamination on the service life of rolling bearings, with an emphasis on developing a more precise calculation methodology that reflects real-world operating conditions. The research provides a critical overview of the current standards and methodologies. Also, this paper examines ISO 281 analytical and empirical methods for rating life calculation while addressing existing limitations. The study aims to enhance the reliability and accuracy of rolling bearing service life prediction.

SYSTEMS APPROACH TO CALCULATION OF BALL BEARING RATING LIFE - FACTOR a_{ISO}

In the current version of the ISO 281 standard /3/, a systematic approach to more precise determination of the rating life of rolling bearings is applied. Such an approach implies consideration of various influences on the bearing service life, through changes and interaction of mutually dependent influencing factors. The standard rating life of a ball rolling bearing is determined based on the expression:

$$L_{nm} = a_1 a_{ISO} \left(\frac{C}{P}\right)^3 \text{ (}10^6\text{ revolutions)}, \quad (1)$$

where: C is dynamic load rating (catalogue data of every single bearing); P is dynamic equivalent load of the bearing, determined based on the supports' reactions by applying appropriate equivalence factors; a_1 is modification factor of reliability, different from 90 % (for 90 % reliability, this factor is $a_1 = 1$); a_{ISO} is a modification factor, based on a systems approach to the calculation of the bearing rating life which depends on the characteristics of the lubricant, lubrication and sealing conditions, level of cleanliness of the environment (lubricant contamination level), fatigue load limit and operating load. An overview of all described parameters that affect the modification factor a_{ISO} is shown in Fig. 1.

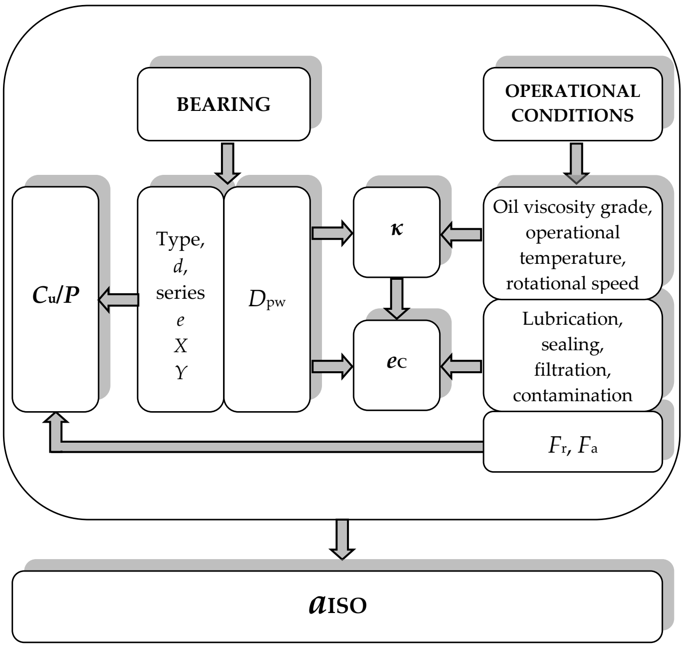


Figure 1. Modification factor of the systems approach to the calculation of rating life.

The factor a_{ISO} depends on the characteristics of the bearing and the operating conditions and is a function of three quantities: the viscosity ratio of the lubricant κ, the contamination factor e_c and the ratio of fatigue load limit C_u (catalogue data for each bearing), and the bearing equivalent operating load P. To determine the viscosity ratio of the lubricant and the contamination factor, one should know the size of the bearing determined by pitch diameter D_{pw} ($D_{pw} = (d + D)/2$, where d and D are bore diameter and outer diameter of the bearing, respectively). Fatigue load limit C_u depends on bearing type, its geometry (size, i.e., diameter d and series), and implicitly on the material properties. The equivalent dynamic load of the bearing P depends on the intensity and character of the external load (radial F_r, axial F_a) and on the parameters of reducing the universal radial and axial support reaction to one equivalent load (X, Y, and e).

$$a_{ISO} = 0.1\left(1-\left(2.5671-\frac{A}{\kappa^B}\right)^{0.83}\left(\frac{e_c C_u}{P}\right)^{1/3}\right)^{-9.3} . \quad (2)$$

The constants A and B in Eq.(2) depend on the bearing type and lubricant viscosity ratio. They are introduced in /6/, and their values are determined based on standard expressions from /3/. An overview of the values of these constants for ball bearings is given in Table 1.

Table 1. Constants A and B, /6/.

Viscosity ratio	A	B
$0.1 \le \kappa < 0.4$	2.2649	0.054381
$0.4 \le \kappa < 1.0$	1.9987	0.190870
$1.0 \le \kappa < 4.0$	1.9987	0.071739

The lubricant viscosity ratio κ is an indicator of the quality of the oil film formation between the contact surfaces of the balls and raceways. If a suitable oil film is formed between the contact surfaces of the bearing, the lubricant must have the minimum required viscosity at the reached normal operating temperature. The effectiveness of the applied lubricant is determined by the degree of separation of contact surfaces at operating temperatures. The condition of separation of contact surfaces is conveniently determined by the value of the viscosity ratio:

$$\kappa = \frac{\nu}{\nu_1}, \quad (3)$$

where: ν is actual kinematic viscosity at operating temperature; ν_1 is a reference kinematic viscosity, required to obtain adequate lubrication condition.

The actual kinematic viscosity at operating temperature of the bearing depends on the type of lubricant and its prescribed viscosity at a certain temperature (lubricant catalogue data). The reference kinematic viscosity is the required viscosity of the lubricant applied to lubricate a bearing of certain dimensions which operates with a certain rotation speed. Most general-purpose rolling bearings are lubricated with oils or greases. Greases are used for lubrication in more than 80 % of rolling bearing applications of all types. According to the standard for the calculation of the rating life, the same expressions and diagrams can be applied in the case of determining the viscosity ratio of grease-lubricated bearings, where the considered viscosity from Eq.(3) refers to the base oil of the applied grease.

BALL BEARING CONTAMINATION - FACTOR e_c

In the calculation of the rolling bearing service life, the influence of contamination of the oil film between contact surfaces of rolling elements and raceways is taken into account by factor e_c. In real operating conditions of rolling bearings, the lubricant contains a certain amount of hard debris particles. The shape, size, concentration and material of the debris particles present in the lubricant depend on the quality of the technological procedure of manufacturing and bearing assembly, the environment, the method of lubrication, the adequacy and efficiency of the method and means of sealing the system and filtering the lubricant. Debris particles present in the lubricant can be of different origins: functional (originating from the bearing environment), technological (not removed after the technological processes of manufacturing bearing parts) and those created during bearing operation, due to contact surface wear. Roller bearings operate in elasto-hydrodynamic (EHD) lubrication mode. The oil film between the rolling elements and the raceways is usually about 1 μm, /7/. Debris particles, whose dimensions are smaller than the oil film thickness, pass with the lubricant through elastohydro-dynamic contact and do not cause surface damage. Most of the debris particles, which can be found in the lubricant, are larger than the oil film thickness and they can enter into various forms of interaction with contact surfaces (Fig. 2), /8, 9/.

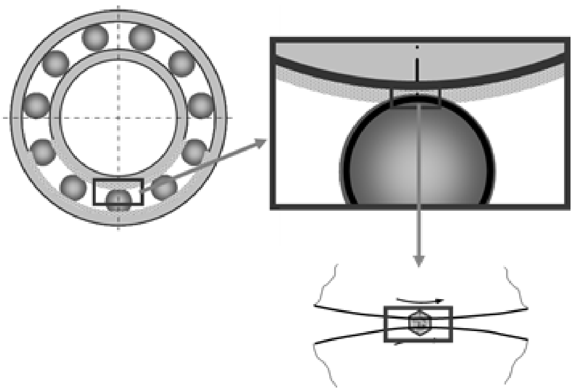


Figure 2. A debris particle between contact surfaces of the bearing.

Some possible interactions of debris particles with contact surfaces are shown in Fig. 3. If the particle has a lower hardness than contact surfaces, it can be crushed (Fig. 3a) or plastically deformed (flattened) to the dimensions of the oil film thickness, i.e., the distance between contact surfaces. The relationship between the strength of the particle and the hardness of contact surfaces can be such that the particle is trapped into one or both contact surfaces. If the contact

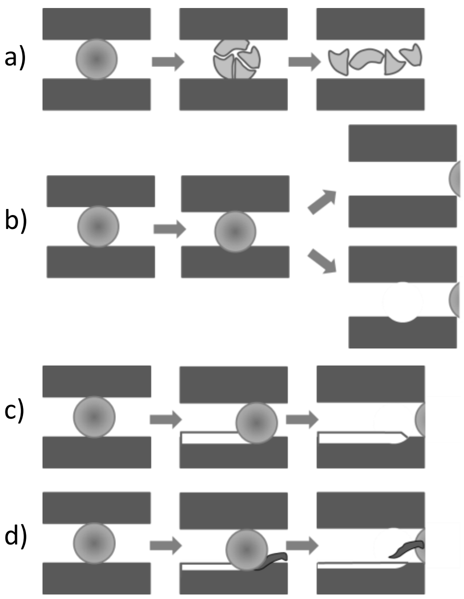


Figure 3. Particle interaction with bearing contact surfaces.

between the particle and contact surfaces is within the limits of elasticity of contact surfaces, the particle leaves the contact, and there are no changes on the contact surfaces themselves. Also, there may be a plastic indentation of a particle of high hardness into the contact surfaces, after which it leaves the contact undamaged. In these cases, the pit remains on contact surfaces (Fig. 3b). A particle can be captured by one of the contact surfaces and cause microscopic plastic grooving of the other contact surface (Fig. 3c). If the particle is non-metallic, mineral origin, with high hardness and sharp edges (has high abrasive capacity), it can perform microscopic cutting of contact surfaces, followed by material separation (Fig. 3d).

All damages, caused as a result of interaction of debris particles with contact surfaces of bearing parts, become sources of stress concentration and initiate the appearance of surface fatigue and further larger damage to bearing parts. This leads to a reduction of the bearing service life. That is why the expression for nominal service life should also include the influence of lubricant contamination. Contamination factor e_c depends on the type, size, hardness and concentration of debris particles in the lubricant, oil film thickness (viscosity ratio κ), as well as on bearing size. Its values are between 0 (very severe contamination) and 1 (extreme cleanliness). According to /3/, expressions are given for determining the contamination factor for different methods of oil and grease lubrication. In /3/, 15 expressions and 14 corresponding diagrams are given for determining the contamination factor for all lubrication methods. The expressions are similar in form, with different values of constants, depending on the method of lubrication and the level of contamination of the lubricant. The general formula for determining the contamination factor, derived based on standard formulas, is presented in the paper /6/:

$$e_c = a\left(1 - \frac{E}{D_{pw}^{1/3}}\right); \quad a = F\kappa^{0.68} D_{pw}^{0.55}, \text{ where } a \le 1. \qquad (4)$$

The values of constants E and F in Eq.(4) are given in Table 2, depending on lubricant contamination, /6/.

Table 2. Constants E and F for ball bearings, /6/.

Level of contamination	E	F
High cleanliness	0.6796	0.0864
Normal cleanliness	1.141	0.0432
Slight to Typical contamination	1.887	0.0177
Severe contamination	2.662	0.0115
Very severe contamination	4.06	0.00617

For grease-lubricated rolling bearings, standard /3/ foresees five levels of lubricant state: high cleanliness, normal cleanliness, slight to typical contamination (in this case the value of contamination factor also depends on the size of the bearing), severe contamination, and very severe contamination. To make it easier for the user to determine the contamination factor of grease for bearing lubrication, appropriate clarification is provided in the standard (Table 3).

According to the expressions and diagrams given in /3/, the contamination factor can be accurately determined for certain operating conditions (lubrication method and contamination level). The diagrams are also valid for mixtures of particles of different hardness and strength, but it is considered that only hard particles (hardness greater than the hardness of contact surfaces) and greater than the thickness of the oil film between contact surfaces affect the service life of the bearing. The presence of other impurity particles is ignored. The standard also provides a table with orientational recommendations for the contamination factor depending on the qualitatively described lubrication and filtering conditions (Table 4). At the same time, for all levels of contamination, it is assumed that the bearings are properly lubricated (there is no starvation).

Table 3. Grease contamination levels, /3/.

Level of grease contamination	Operating conditions
High cleanliness	Very clean assembly, carefully washed; very good sealing; regreasing done regularly and at short intervals. Sealed bearings, lubricated for the entire life, with effective sealing, according to operating conditions
Normal cleanliness	Clean assembly with flushing; good sealing; regreasing according to the manufacturer's recommendations. Sealed bearings, lubricated for the entire working life with proper sealing (bearings with sealing shields)
Slight to typical contamination	Clean assembly; medium sealing; regreasing according to the manufacturer's recommendations
Severe contamination	Assembly in a workshop; bearing is not adequately washed after assembly; poor sealing; regreasing at intervals, which are longer than recommended by the manufacturer
Very severe contamination	The assembly is in a contaminated environment; inadequate sealing; long regreasing intervals

Table 4. Contamination factor e_c /3/.

Level of contamination	D_{pw}	
	< 100 mm	≥ 100 mm
Extreme cleanliness The particle size is within the limits of the oil film thickness; laboratory conditions	1	
High cleanliness An extremely fine filter; bearings lubricated with grease for a lifetime and well-sealed	0.8 ... 0.6	0.9 ... 0.8
Normal cleanliness Fine filter; conditions typical of bearings lubricated with grease for a lifetime and sealed with shields	0.6 ... 0.5	0.8 ... 0.6
Slight contamination	0.5 ... 0.3	0.6 ... 0.4
Typical contamination No built-in seals; course filtering; particles - wear products of other parts of the machine system	0.3 ... 0.1	0.4 ... 0.2
Severe contamination The bearing environment is heavily contaminated, and the bearing has inadequate sealing	0.1 ... 0	0.1 ... 0
Very severe contamination	0	

Bearing manufacturers also provide this table in their catalogues /10, 11/. To be able to apply all the mentioned standard recommendations, for the most accurate possible life assessment, it is necessary that bearings operate under the expected conditions, already from the very first start of the machine, as well as after introducing new lubricant into the lubrication system. In addition, it is very important to thoroughly rinse the bearings after assembly, especially when bearings are expected to operate in the cleanest conditions. These are all the starting assumptions of the standard and any deviation from expected operating conditions may lead to the fact that the calculation of the expected life, according to the proposed standard procedure, will not be correct, i.e., the calculation of service life will not be reliable enough.

The question arises, what are the deviations of the quasi-real values of factor e_c calculated using Eq.(4) and the recommended empirical values of this factor, according to Table 4. Based on Eq.(4), appropriate diagrams are shown in Figs. 4-8.

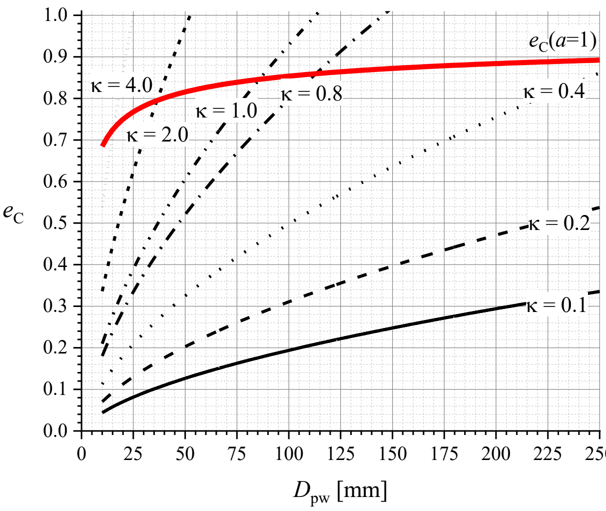


Figure 4. Lubricant contamination factor vs. bearing size and viscosity ratio – high cleanliness of lubricant.

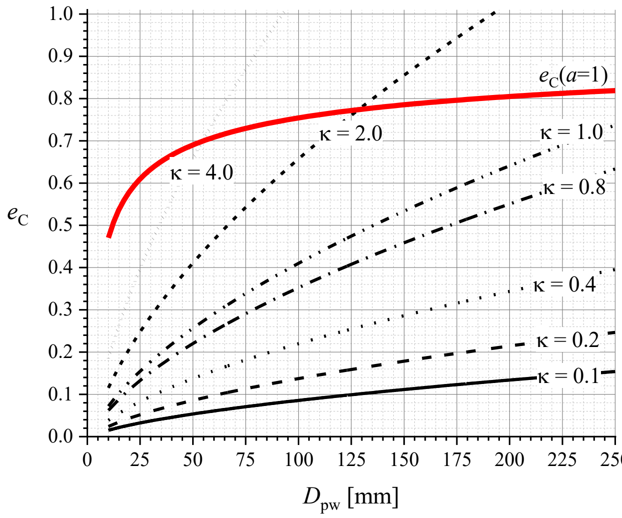


Figure 5. Lubricant contamination factor vs. bearing size and viscosity ratio – normal cleanliness of lubricant.

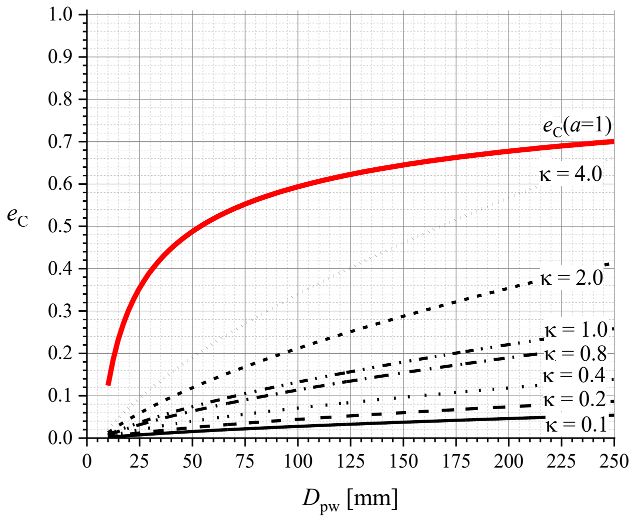


Figure 6. Lubricant contamination factor vs. bearing size and viscosity ratio - slight to typical contamination of lubricant.

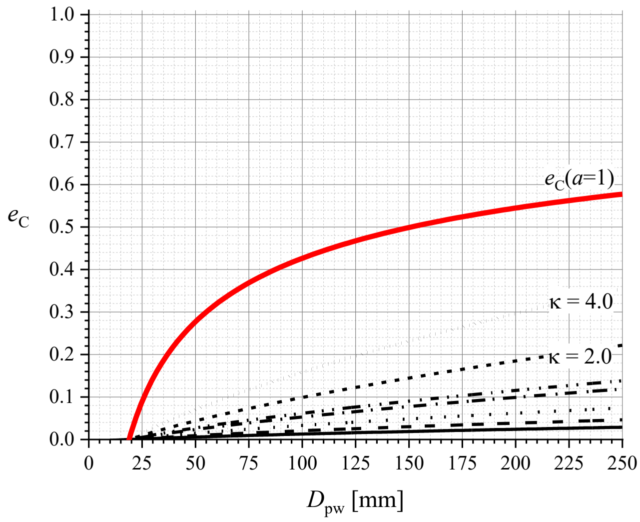


Figure 7. Lubricant contamination factor vs. bearing size and viscosity ratio – severe contamination of lubricant.

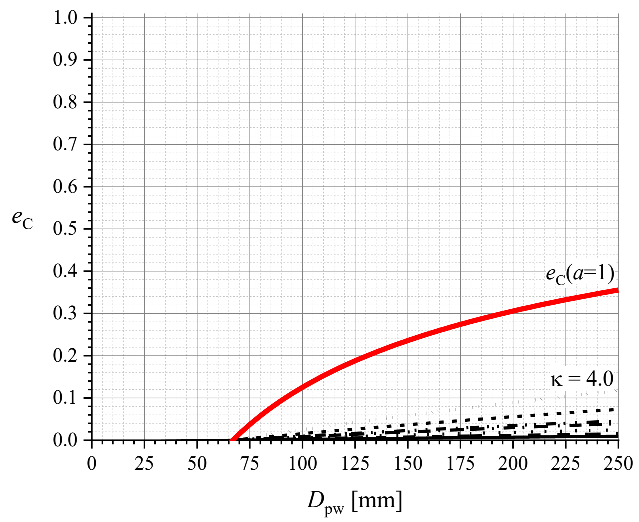


Figure 8. Lubricant contamination factor vs. bearing size and viscosity ratio – very severe contamination of lubricant.

Diagrams in Figs. 4-8 show how the lubricant contamination factor depends on bearing size (determined by bearing pitch diameter D_{pw}), the lubricant viscosity ratio κ and the level of lubricant contamination. The bearings with a pitch diameter (10...250) mm are considered.

By analysing these diagrams, the following is concluded:
- the value of contamination factor increases with increase in the size of bearing, lubricant viscosity ratio and lubricant contamination;
- mathematically, the lubricant contamination factor can be greater than 1, but its real values are less than 1 due to the limitation determined by the auxiliary quantity $a = 1$ (red 'roof' line in the diagrams);
- in cases of severe lubricant contamination (for bearings with a pitch diameter of less than 20 mm) and very severe lubricant contamination (for bearings with a pitch diameter of less than 65 mm), the contamination factor has zero values which means that small bearings can hardly withstand the conditions of heavy contamination lubricants;
- in cases of high and normal lubricant cleanliness, combinations of bearing size and viscosity ratio are possible such that the contamination factor has values up to 0.8...0.85;
- regardless of bearing size and viscosity ratio, in the case of typical contamination, the contamination factor does not exceed 0.7, in the case of severe contamination it can be at most 0.35, and in the case of very severe contamination, it is below 0.12.

The values of the contamination factor, depending on the bearing size and qualitative description of the level of contamination, based on data in Table 4, are shown in Fig. 9. The effect of lubricant viscosity is not taken into account here. Based on a comparative analysis of diagrams in Figs. 4-8 and the diagram in Fig. 9, it can be stated that the diagram in Fig. 9 is formed based on approximate values determined by boundary red lines in Figs. 4-8. So, the standard recommended values of the lubricant contamination factor are the highest possible limit values of the mathematical model given by Eq.(4). From the conducted analysis, the conclusion follows that recommended values of the contamination factor from Table 4 can only be used in approximate predictions of the bearing service life, and not for exact calculations of the rating life.

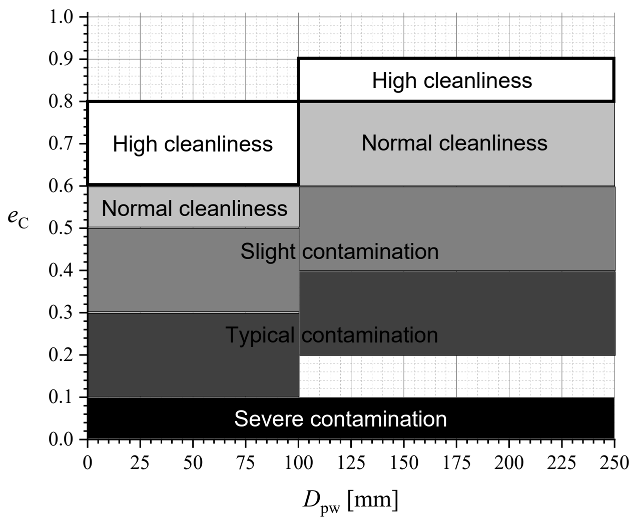


Figure 9. Lubricant contamination factor vs. bearing size according to Table 4.

NUMERICAL EXAMPLE AND RESULTS DISCUSSION

The rating life of rolling bearings is directly proportional to the system access factor a_{ISO}, according to Eq.(1). In addition, the rating life also depends on the ratio of bearing dynamic load rating and its equivalent operating load, i.e., on the C/P ratio. Factor a_{ISO} depends on the ratio of the fatigue load limit and equivalent load, i.e., the C_u/P ratio, according to Fig. 1 and Eq.(2). The dynamic load rating C and fatigue load limit C_u are characteristics of each bearing and are given in manufacturer's catalogues, depending on the type and size of bearing. Therefore, further analysis of the influence of lubricant contamination on the modification factor of the systems approach and rating life should be performed using a numerical example.

The deep groove ball bearing 6306 is analysed in this paper. The basic characteristics (catalogue data) of this bearing are bore diameter d = 30 mm; and outer diameter D = 72 mm; pitch diameter D_{pw} = 51 mm; dynamic load rating C = 29.6 kN, fatigue load limit C_u = 0.67 kN.

Based on Eq.(4) the diagram in Fig. 10 is made for considered deep groove ball bearing. Based on this diagram, it can be concluded that the auxiliary quantity a increases with the increase of lubricant cleanliness and viscosity ratio. The value of a cannot be greater than 1, /3/. Only in the case of high lubricant cleanliness and at a viscosity ratio of 1.5, this quantity reaches the value of 1. The sensitivity of a to the lubricant cleanliness is greater in the case of a higher viscosity ratio of grease base oil.

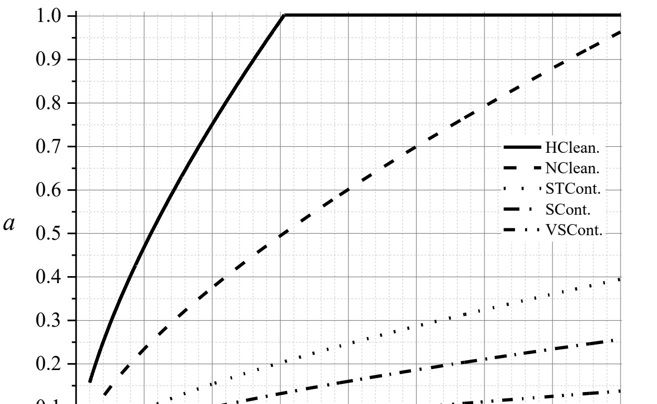


Figure 10. Auxiliary quantity of lubricant contamination factor of bearing 6306 vs. viscosity ratio and oil contamination level.

The diagram of a is necessary to determine the limit value of minimum viscosity ratio when a = 1. This means that for a viscosity ratio greater than 1.5, the lubricant contamination factor e_c has an adequate constant maximum value. The diagram of the contamination factor depending on viscosity ratio and lubricant contamination level is shown in Fig. 11. In this diagram it can be seen that the highest value that the contamination factor can have in the case of bearing 6306 is e_c = 0.82. This is in accordance with Table 4, for the case of high lubricant cleanliness. In the case of extreme cleanliness, the contamination factor is e_c = 1, but that value is unattainable. According to this diagram, the contamination factor increases with increasing lubricant cleanliness and viscosity ratio. As in the case of auxiliary size a, this bearing is more sensitive to lubricant contamination, if the viscosity ratio is higher.

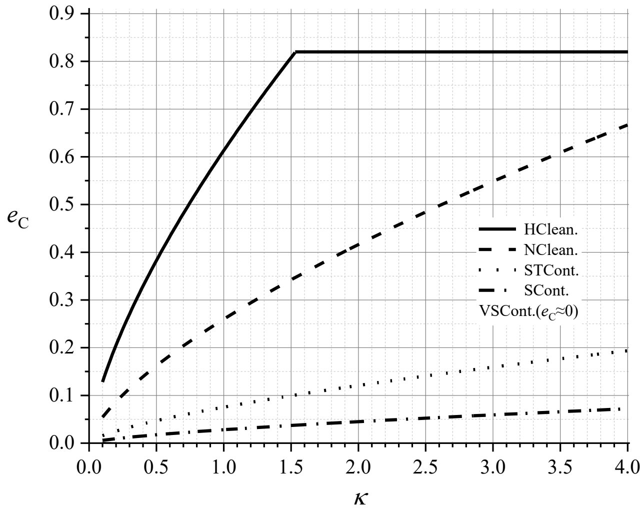


Figure 11. Lubricant contamination factor of bearing 6306 vs. viscosity ratio and oil contamination level.

According to Eq.(2), the modification factor of the system approach a_{ISO} depends on the contamination factor e_c and the ratio of fatigue load limit and operating load of the bearing C_u/P. In further analyses, three specific bearing load cases are considered: light load (equivalent operating load of the bearing is 10 % of bearing's dynamic load rating, i.e., $P = 0.1C$), medium load ($P = 0.5C$) and heavy load ($P = C$). The values of C_u/P ratio according to the specified loading conditions are shown in Table 5.

Table 5. Loading conditions of bearing 6306.

C/P	P (kN)	C_u/P
0.1	2.96	0.0226
0.5	14.80	0.0453
1.0	29.60	0.2260

Based on Eqs.(2) and (4), as well as Tables 2 and 5, diagrams are drawn, shown in Figs. 12-14. Based on these diagrams, it is concluded:
- the modification factor of systems approach a_{ISO} increases with an increase in viscosity ratio and lubricant cleanliness and with a decrease in the load;
- the minimum value of a_{ISO} factor is 0.1 and it corresponds to very severe contamination (high concentration of debris particles and poor sealing);
- in case of high cleanliness of the lubricant, at values of viscosity ratio greater than 2.5, the maximal value of factor a_{ISO} is reached, which is 50, meaning that the bearing operating in conditions of a very clean environment and under low load can have 50 times (!) greater life from the value of the basic rating life;
- in the case of normal lubricant cleanliness and high lubricant viscosity ratio (e.g., κ = 4), for a bearing operating under light load, the a_{ISO} factor can reach a value of approx. 17;
- when the bearing operates under medium load, the a_{ISO} factor can have maximum values: 4.0 with high lubricant cleanliness, 1.5 with normal lubricant cleanliness, 0.5 and 0.3 with typical and severe contamination, respectively;

- when the bearing operates under a heavy load, the a_{ISO} factor can have a maximum value of 1.7 with high lubricant cleanliness, and for all other levels of lubricant contamination and all viscosity ratios it is less than 1;
- in all cases of such a combination of lubricant contamination level and viscosity ratio when $a_{ISO} < 1$, the rating life is shorter than the rating life determined by applying the basic rating life formula.

The dependence of rating life on the load and the level of contamination is not linear. Nominal service life, according to Eq.(1), depends on the load, the ratio C/P dynamic load capacity and equivalent operating load of the bearing, as well as on the value of service life modification factor a_{ISO}.

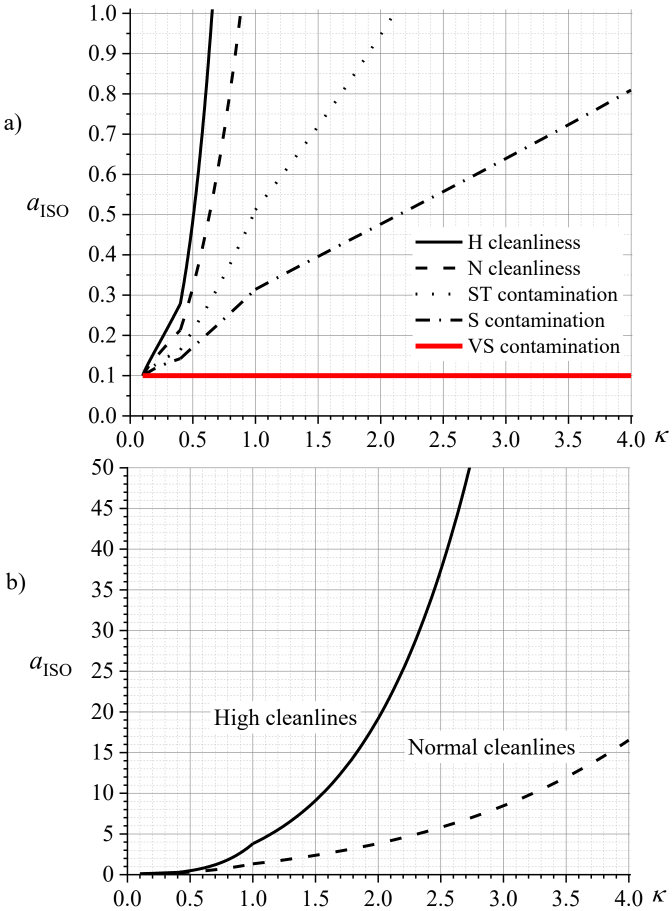
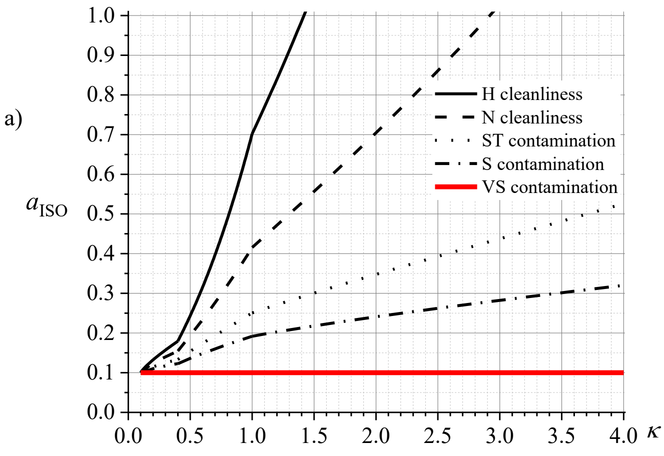


Figure 12. Modification factor of systems approach vs. viscosity ratio and level of oil contamination (operating load $P = 0.1C$).



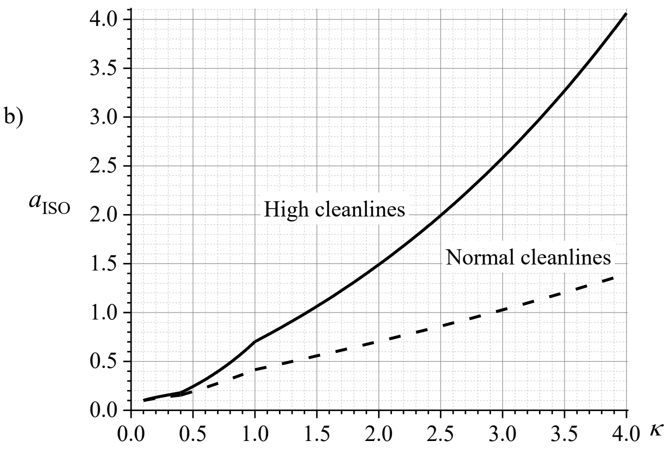


Figure 13. Modification factor of systems approach vs. viscosity ratio and level of oil contamination (operating load P = 0.5C)

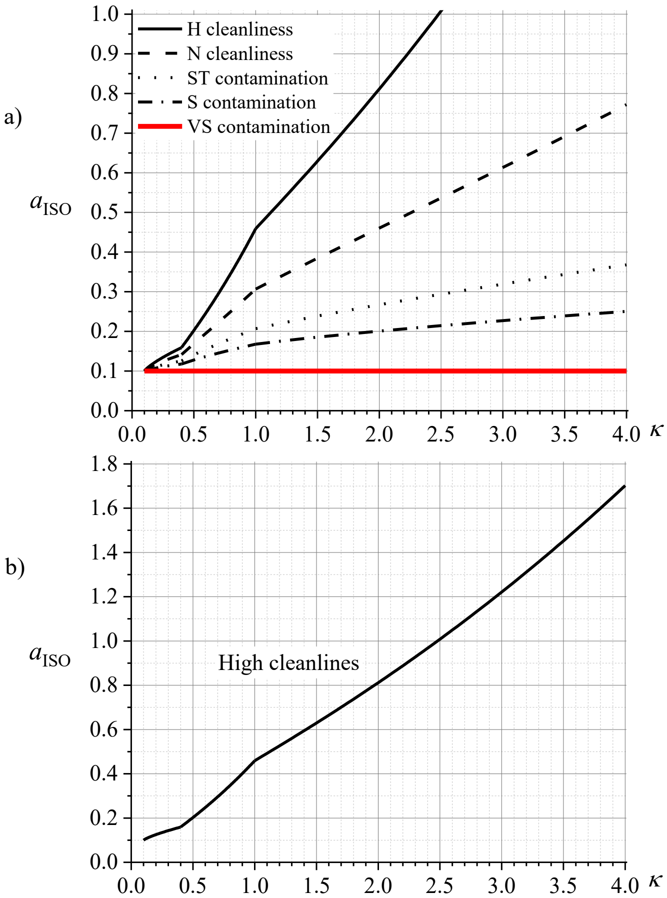


Figure 14. Modification factor of systems approach vs. viscosity ratio and level of oil contamination (operating load P = C).

At the same time, the a_{ISO} factor also depends on the bearing operating load. Considering that the operating loads ($0.1C$, $0.5C$ and $1.0C$) are given, in Eq.(1), the ratio $(C/P)^3$ will be 1000, 8, and 1. If these values are multiplied by the values of a_{ISO}, the service life expressed by the number of load cycles, i.e., millions of revolutions is obtained.

CONCLUSIONS

The research highlights the importance of accurately calculating the contamination factor, demonstrating its dependence on bearing size, lubricant viscosity, and lubricant cleanliness/contamination levels. The numerical example confirms that cleaner lubricants and reduced loads significantly enhance the modification factor thus prolonging bearing service life. However, under severe contamination conditions, particularly for smaller bearings, service life predictions become unreliable, emphasizing the critical role of proper lubrication and sealing. The paper shows that the ISO 281 standard provides two methods for determining the contamination factor: analytically, through the use of specific formulas, and empirically, via numerical recommendations for various bearing operating conditions. The analysis indicates that while empirical recommendations encompass all possible operational conditions, they can, in some cases, underestimate the actual service life of the bearing. Consequently, it is concluded that analytical expressions should be employed for precise calculations to accurately determine rolling bearing rating life.

This work validates the mathematical models provided by ISO standards and recommends their integration into practical engineering applications to ensure precision in bearing life estimations. The results underscore the need for ongoing refinement of standards to address real-world operational complexities, thereby improving reliability and efficiency in mechanical systems.

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