Evolution of rolling bearing life rating through the standardization

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Abstract: *The operational ability of a rolling bearing selected for a specific application is assessed based on service life. The basic formula for bearing rating life was established more than 70 years ago by A. Palmgren. The first standard presenting a basic mathematical model for rating life calculation was published in 1962 (ISO/R281). The content of this standard has been revised and the next version was published in 1977 (ISO 281-1). The novelty was the introduction of adjustment factors for reliability other than 90%. This standard was replaced by the ISO 281 standard in 1990, which introduced additional adjustment factors for special bearing properties and operating conditions. The latest version of the ISO 281 standard was published in 2007. This standard provides a procedure for calculating the modified service life by taking into account the additional impacts of lubrication condition, lubricant contamination and limit fatigue load. Furthermore, the document ISO/TS 16281 was published in 2008 introducing the influence of bearing internal clearance and misalignment in the rating life calculation. An overview of the development of a standardized formula for bearing rating life is given in this paper, on the example of deep groove ball bearing under radial operational loading.*

Keywords*: ROLLING BEARINGS, RATING LIFE, ADJUSTED RATING LIFE, MODIFIED RATING LIFE, STANDARDIZATION, ISO*

1. Introduction

A first discussion on the international level on standardization of the calculation method for load ratings of rolling bearings took place at the conference of the International Federation of the National Standardizing Associations (ISA) held in 1934 [1,2]. The first proposals for the definition of the fundamental concept to load rating and life calculation standards were included in the ISA 1945 report on the state of rolling bearing standardization. This report was distributed in 1949 as a document of Technical Committee ISO/TC 4 and the definitions it contained are in essence those given in ISO 281:2007 [3], which is the last version of the standard on the bearing life and basic dynamic load rating concepts. These concepts are based on the theory of Palmgren and Lundberg, using Weibul statistics [4-6]. The first proposal to ISO named “Load rating of ball bearings” was presented in 1950. After that, load rating and life calculation methods were studied by ISO Technical committee 4 at eleven meetings from 1951 to 1959. Finally, The draft ISO Recommendation was issued in 1959, and ISO/R281 was accepted by ISO Council in 1962 [1,2].

In 1964, the member body from Sweden suggested that ISO/R281 has to be reviewed and submitted proposal considering the development of imposed bearing steels, which was not accepted from the technical committee. Three years later, the technical committee accepted a suggestion by the member body from Japan to do a revision of ISO/R281. The member body from the USA submitted the Draft AFMBA (Anti-Friction Bearing Manufacturers Association) standard “Load ratings and fatigue life for ball bearings” for consideration in 1970 and “Load ratings and fatigue life for roller bearings” in 1971. These proposals were investigated in detail at five meetings from 1971 to 1974 [1,2]. The third and the final Draft proposal was circulated as a Draft International Standard in 1976 and became ISO 281-1:1977. The major part of it was almost the same as ISO/R281, but, based on American investigations during the ’60s, a new clause was added, dealing with adjustment of rating lifer for reliability other than 90% and for material and operating conditions [1,2]. Furthermore, supplementary theoretical background with a derivation of mathematical expressions and new factors given in ISO 281-1:1977 was published first as ISO 281-2 “Explanatory notes” in 1979 and later as ISO/TR 8646:1985 [1].

The International Standard ISO 281:1990 [7] specifies methods of calculating the basic dynamic load rating of rolling bearings manufactured from contemporary, commonly used, good quality hardened steel in accordance with good manufacturing practice and basically of conventional design, which life is associated with 90% reliability. In addition, this version of standard ISO 281 specifies calculation adjusted rating life for various reliabilities, special bearing properties and specific operating conditions. These influences are taken into account by life adjustment factors. Detailed background information regarding the derivation of formulae and factors given for this standard are found in ISO/TR 8646 [1], as it was used for the previous version as well. The Technical Specification ISO/TS 16799 published in 1999 [8] introducing different factors in the calculation of basic dynamic load ratings and equivalent load for radial and thrust angular-contact ball bearings.

ISO 281:2007 [3] specifies methods for calculating the basic rating life, which is the life associated with 90% reliability, with commonly used high quality material, good manufacturing quality and with conventional operating conditions. In addition, it gives calculating procedure for modified rating life, for reliabilities other than 90%, specific lubrication conditions, lubricant contamination, as well as fatigue load limit of the bearing raceways. Background information regarding the derivation of equations and factors in this standard is given in two technical specifications ISO/TS 1281-1 [1] and ISO/TS 1281-2 [9] published in 2008. The first edition of ISO/TR 1281-1 “Explanatory notes – Basic dynamic load rating and basic rating life” cancels and replaces the first edition of ISO/TR 8646:1985, which has been technically revised. The first edition of ISO/TR 1281-2 “Explanatory notes – Modified rating life calculation, based on a system approach to fatigue stresses” gives background information regarding the derivation life modification factors. Calculation method given in ISO 281:2007 does not consider the influence of tilted or misaligned rings and bearing clearance on the service life. The Technical Specification ISO/TS 16281:2008 describes and advanced calculation method, which considers tilting or misalignment, operating clearance and internal load distribution between rolling elements [10], but only as information for computer calculation. There is no completed a mathematical model for any modification factor to be used in life prediction calculation method. For example, the factor of the influence of internal radial clearance in radially loaded ball bearing would have values 0.3…1.0 depending on load and clearance, as it is shown in [11]. Surely, revisions of ISO standard for dynamic load ratings and rating life will be required from time to time, as the result of new scientific developments or newly obtained information concerning specific bearing types and materials [3].

An overview of ISO 281 standards for rolling bearings dynamic load rating and rating life with appropriate explanatory notes in the form of additional technical specifications to which the standards refer is made in this paper. The standard procedure for calculating the basic service life [7,3], adjusted service life [7] and modified service life [3] is presented, taking into account the influence of reliability, lubrication, contamination and fatigue load limit. A numerical example was made for the purpose of comparative analysis of the standardized calculation and the calculation using the data of the rolling bearings manufacturers.

2. ISO 281:1990

2.1. Basic rating life

The basic rating life of radial deep groove ball bearing is given by

$$L_{10} = \left(\frac{C_r}{P_r} \right)^3 , \quad (1)$$

where C_r is basic dynamic radial load rating, P_r – dynamic equivalent radial load.

Subscript "10" is the probability of failure (in %) and gives information on reliability. The standard basic life formula is derived under the assumption of 90% reliability, which means that for a group of apparently identical rolling bearings, operating under the same conditions, 90% of the group is expected to attain or exceed a specified service life.

The basic dynamic radial load rating for radial contact ball bearings is given by:

$$C_r = b_m f_c Z^{2/3} D_w^{1,8} , \quad (2)$$

where b_m is the rating factor for contemporary, normally used material and manufacturing quality, depending on bearing type and design, f_c – the factor which depends on the geometry of the bearing components, the accuracy to which the various components are made, and the material, Z - number of balls, D_w – ball diameter.

Values of rating factor b_m are table data [7] and for radial deep groove ball bearings b_m=1,3. Values of f_c factor are also given in appropriate standard table [7] for different bearing types and ratio D_w/D_{pw}, where D_{pw} is pitch diameter of ball set. Instead, the mean bearing diameter $0.5(d + D)$ can also be used, where d is bearing bore diameter and D is bearing outside diameter.

Dynamic equivalent radial load P_r for radial contact ball bearing, under constant radial and axial loads is given by

$$P_r = XF_r + YF_a , \quad (3)$$

where X and Y are dynamic factors, radial and axial, respectively (given in standard tables [7]), F_r and F_a – bearing radial and axial load (radial and axial components of actual bearing load), respectively.

In the case of deep groove ball bearing loaded with pure radial external load F_r, the equivalent load is

$$P_r = F_r . \quad (4)$$

2.2. Adjusted rating life

The adjusted bearing life is actually the basic rating life, given by Eq.(1), adjusted for the reliability of (100 - n)%, for special bearing properties and for specific operating conditions:

$$L_{na} = a_1 a_2 a_3 L_{10} , \quad (5)$$

where a_1 is life adjustment factor for reliability, a_2 - life adjustment factor for special bearing properties, a_3 - life adjustment factor for operating conditions.

Values of a_1 factor are given in standard tables [7], depending on required reliability (90…95)%, since values of a_2 and a_3 factors are discussed only. In accordance with contemporary bearing technology, rolling bearings could be made by the use of a special type and quality of material and/or special manufacturing process and/or special design. These special properties are taken into account by the adjustment factor a_2. The values of this factor are mostly based on experience and could be obtained from the bearing manufacturers [7].

The life adjustment factor a_3 takes into account the influence of adequacy of the lubricant and lubrication system, contamination, and conditions causing changes in material properties. The standard recommends that bearing manufacturers provide appropriate values of a_3 in accordance with the specific application and used bearing type.

3. ISO 281:2007

3.1. Modified rating life

The modified rating life equation for the rolling bearing is

$$L_{nm} = a_1 a_{ISO} L_{10} , \quad (6)$$

where L_{10} is basic rating life, given by Eq.1, a_1 - modification factor for reliability, a_{ISO} – modification factor for system approach.

It is important to know that the a_1 values for the reliabilities 95% to 99% have been modified compared with the corresponding values in the ISO 281:1990. Furthermore, the table with a_1 values is extended to 99,95%. In the period between the last two editions of standard ISO 281, a practical method was developed for performing modified life systems approach calculations by introduction a_{ISO} factor. This factor considers the fatigue stress limit of the bearing steel and also the influence of lubrication and contamination on bearing service life.

3.2. Life modification factor a_{ISO}

The life modification factor for a system approach is determined by analytical investigations, empirical laboratory tests and practical experience. Besides bearing type, fatigue load and bearing operational load, the factor a_{ISO} considers the influence of [3]: lubricant (the type of bearing size and speed, lubricant, viscosity, additives); environment (seals, contamination level); contaminant particles (hardness and particle size in relation to bearing size, lubrication method, filtration), and cleanliness during mounting.

The life modification factor a_{ISO} for radial ball bearings can be calculated with equation [3]

$$a_{ISO} = 0.1 \left(1 - \left(2.5671 - \frac{A}{\kappa^B} \right)^{0.83} \left(\frac{e_C C_u}{P} \right)^{\frac{1}{3}} \right)^{-9.3} , \quad (7)$$

where κ is viscosity ratio, e_C - contamination factor, C_u – fatigue load limit, P – dynamic equivalent load, A and B – constants depending on viscosity ratio values (Table 1).

Table 1: *Constants A and B in Eq.7 depending on viscosity ratio κ*

	A	B
$0.1 \le \kappa < 0.4$	2.2649	0.054381
$0.4 \le \kappa < 1$	1.9987	0.19087
$1 \le \kappa \le 4$	1.9987	0.071739

Viscosity ratio is given by

$$\kappa = \frac{\nu}{\nu_1} , \quad (8)$$

where ν is the actual kinematic viscosity of the lubricant at operating temperature, ν_1 – reference kinematic viscosity at operating temperature. In the case of greases, these are operating viscosities of the base oil.

The actual kinematic viscosity of the lubricant at operating temperature is estimated based on the operating temperature and the viscosity of applied lubricant at temperature of 40 °C, using diagrams from catalogues of bearing manufacturers [13,14] or oil and grease manufacturers.

The reference kinematic viscosity can be calculated with following equations [3]

$$\begin{aligned} \nu_1 &= 45000 n^{-0.83} D_{pw}^{-0.5} \quad \text{for } n < 1000 \text{ r/min} \\ \nu_1 &= 4500 n^{-0.5} D_{pw}^{-0.5} \quad \text{for } n \ge 1000 \text{ r/min} \end{aligned} , \quad (9)$$

where n is bearing speed, D_{pw} - pitch diameter of ball set (or mean bearing diameter).

The contamination factor e_C takes into account bearing life reduction caused by solid particles in the lubricant film. It is dependent on type, size, hardness and quantity of the particles, on lubricant film thickness (viscosity ratio κ), as well as on bearing size. Its value varies from 0 (very severe contamination) to 1 (extreme cleanliness). In the transition between normal cleanliness (oil filtered through fine filter; conditions typical of greased and shielded bearing) and slight contamination in the lubricant, contamination factor is about 0.5 [3]. A simplified method to estimate e_C is given in standard using the appropriate qualitative table, but also there is an annex in the standard which provides a more advanced and detailed method to calculate the e_C factor. In accordance with this annex, the contamination factors can be determined for following lubricant methods: circulating online filtered oil, oil bath or offline filtered circulating oil, and grease lubrication. The general formula for the contamination factor is

$$e_C = a\left(1 - \frac{E}{D_{pw}^{1/3}}\right);$$
$$a = F\kappa^{0.68} D_{pw}^{0.55} \quad \text{with restriction } a \le 1, \tag{10}$$

where E and F are constants depending on lubrication method (Table 2).

Table 2: *Constants C and E in Eq.10 depending on the lubricant method*

	E	*F*
Circulating oil lubrication with online filters		
$\beta_{6(c)}$=200; ISO 4406 code –/13/10	0.5663	0.0864
$\beta_{6(c)}$=200; ISO 4406 code –/15/12	0.9987	0.0432
$\beta_{25(c)}\geq$75; ISO 4406 code –/17/14	1.6329	0.0288
$\beta_{25(c)}\geq$75; ISO 4406 code –/19/16	2.3362	0.0216
Oil lubrication without filtration or with offline filters		
ISO 4406 code –/13/10	0.6796	0.0864
ISO 4406 code –/15/12	1.141	0.0288
ISO 4406 code –/17/14	1.67	0.0133
ISO 4406 code –/19/16	2.5164	0.00864
ISO 4406 code –/21/18	3.8974	0.00411
Grease lubrication		
High cleanliness	0.6796	0.0864
Normal cleanliness	1.141	0.0432
Slight to typical contamination D_{pw} < 500mm	1.887	0.0177
Slight to typical contamination $D_{pw} \geq$ 500mm	1.677	0.0177
Severe contamination	2.662	0.0115
Very severe contamination	4.06	0.00617

The quantity $\beta_{x(c)}$ in Table 2 is the filtration ratio at contamination particle size x in µm according to ISO 16889 ("Hydraulic fluid power filters – Multi-pass method for evaluating filtration performance of a filter element"). The contamination levels for a range of cleanliness codes are defined in ISO 4406 ("Hydraulic fluid power – Fluids – Methods for coding the level of contamination by solid particles").

The fatigue load limit C_u is defined as the load at which the fatigue stress limit σ_u is reached in the contact between the raceway and most heavily loaded ball in bearing. For rolling bearings of commonly used high quality material and good manufacturing quality, the fatigue stress limit is reached at contact stress of approximately 1500 MPa [3]. This stress value takes into account additional stresses caused by manufacturing tolerances and operational conditions, but in many applications actual contact stresses are larger than fatigue stress limit reducing bearing life.

The fatigue load limit C_u for ball bearing is given by

$$C_u = 0.2288 Z Q_u \quad \text{for } D_{pw} \le 100 \text{ mm};$$
$$C_u = 0.2288 Z Q_u \left(\frac{100}{D_{pw}}\right)^{0.5} \quad \text{for } D_{pw} > 100 \text{ mm}, \tag{11}$$

where Q_u is the fatigue load limit of a single contact.

The fatigue load limit Q_u is the minimum fatigue load limit of the highest loaded contact (contact between the mostly loaded ball and one of the raceways):

$$Q_u = \min\left(Q_{ui}, Q_{ue}\right), \tag{12}$$

where $Q_{ui,\ e}$ are fatigue load limit at a single inner ring raceway contact and a single outer ring raceway contact.

An advanced method for calculating the fatigue load limit C_u is described in [3]. The simplified equations to estimate this quantity are given as well:

$$C_u = \frac{C_0}{22} \quad \text{for } D_{pw} \le 100 \text{ mm};$$
$$C_u = \frac{C_0}{22}\left(\frac{100}{D_{pw}}\right)^{0.5} \quad \text{for } D_{pw} > 100 \text{ mm}, \tag{13}$$

where C_0 is basic static load rating.

The static load rating for ball bearing can be calculated in accordance with [12]

$$C_0 = f_0 Z D_w^2, \tag{14}$$

where f_0 is the factor which depends on the geometry of the bearing components, given in standard tables.

The results of the simplified estimation of fatigue load limit can differ from the results of advanced method which is preferred [3].

4. Numerical example

A numerical example was made in order to apply a standard method for calculating life modification factor for system approach. The factor a_{ISO} was estimated for four bearings of the same bore diameter (30 mm) and of different series (60, 62, 63 and 64).

Table 3: *Estimation of the life modification factor for the system approach*

	Estim.	**6006**	**6206**	**6306**	**6406**
d, mm	-	30	30	30	30
D, mm	-	55	62	72	90
Z	-	11	9	8	7
D_w	-	7.144	9.525	12.303	16.669
D_{pw}	$0.5(d + D)$	42.5	46	51	60
D_w/D_{pw}	-	0.17	0.21	0.24	0.28
f_c	[3]	59.8	59.8	59.0	57.1
b_m	[3]	1.3	1.3	1.3	1.3
C_r, kN	Eq.2	13.2	19.4	28.1	43.0
f_0	[12]	14.7	13.7	13.0	12.1
C_0, kN	Eq.14	8.3	11.2	15.7	23.5
C_u, kN	Eq.13	0.377	0.509	0.714	1.068
P_r, kN	$0.5C_r$	6.6	9.7	14.05	21.5
ν, mm^2/s	[13,14]	16	16	16	16
ν_1, mm^2/s	Eq.9	21.83	20.98	19.93	18.37
κ	Eq.8	0.7	0.8	0.8	0.9
E	Table 2	1.141	1.141	1.141	1.141
F	Table 2	0.0432	0.0432	0.0432	0.0432
a	Eq.10	0.2665	0.3049	0.3227	0.3823
A	Table 1	1.9987	1.9987	1.9987	1.9987
B	Table 1	0.19087	0.19087	0.19087	0.19087
e_C	Eq.10	0.1794	0.2078	0.2234	0.2709
$\boldsymbol{a_{ISO}}$	Eq.7	**0.285**	**0.331**	**0.337**	**0.364**

The external geometry parameters (bore diameter and outside diameter) of these bearings are known from the manufacturer's catalogues [13,14]. The authors of this paper have the appropriate data of internal geometry (number and diameter of balls in considered bearings). Based on these geometric parameters, the standard dynamic and static load ratings were determined (Table 3). All bearings are subjected to the same relative load (half of its own dynamic load capacity). The lubricant is the grease of normal cleanliness. The viscosity of base oil at 40 °C is 80 mm^2/s. It is assumed that the operating temperature is 80 °C and the operating bearing speed is 1000 rpm.

Based on the results shown in Table 3, it can be concluded that under the same operating conditions, the contamination factor e_C and the life modification factor a_{ISO} increase with increasing series of bearings due to the influence of the rolling element size and fatigue load limit. The values of the life modification factor are 0.285…0.364 depending on the bearing series. This means that the reduction of the modified rating life in relation to the basic service life is approx. (64…72)% even in the case of normal lubricant cleanliness (!). Therefore, the factor a_{ISO} must always be taken into the account in the calculation of the bearing service life.

A comparative overview of the calculation of bearing basic and modified rating life according to ISO and two bearing manufacturers is given i Table 4.

Table 4: *Deep groove ball bearing life comparison*

	Estim.	**6006**	**6206**	**6306**	**6406**
ISO 281:2007					
C_r, kN	Eq.2, T.3	13.2	19.4	28.1	43.0
C_0, kN	Eq.14, T.3	8.3	11.2	15.7	23.5
C_u, kN	Eq.13, T.3	0.377	0.509	0.714	1.068
C_0/C_u	-	22	22	22	22
a_{ISO}	Eq.7, T.3	0.285	0.331	0.337	0.364
P_r, kN	$0.5C_r$ *	6.6	9.7	14.05	21.5
L_{10}, 10^6	Eq.1	8	8	8	8
$\mathbf{L_{m\,10}}$, $\mathbf{10^6}$	Eq.6	**2.28**	**2.65**	**2.70**	**2.91**
Manufacturer A					
C_r, kN	Catalogue	13.8	20.3	29.6	43.6
C_0, kN	Catalogue	8.3	11.2	16	23.6
C_u, kN	Catalogue	0.355	0.475	0.670	1.000
C_0/C_u	-	23.4	23.6	23.9	23.6
a_{ISO}	Eq.7	0.281	0.322	0.328	0.393
P_r, kN	(*)	6.6	9.7	14.05	21.5
L_{10}, 10^6	Eq.1	9.14	9.17	9.35	8.34
$\mathbf{L_{m\,10}}$, $\mathbf{10^6}$	Eq.6	**2.57**	**2.95**	**3.07**	**3.28**
Manufacturer B					
C_r, kN	Catalogue	12.7	19.3	29	42.5
C_0, kN	Catalogue	8.0	11.2	16.3	25
C_u, kN	Catalogue	0.390	0.680	1.020	1.640
C_0/C_u	-	20.5	16.5	16.0	15.2
a_{ISO}	Eq.7	0.291	0.378	0.398	0.514
P_r, kN	(*)	6.6	9.7	14.05	21.5
L_{10}, 10^6	Eq.1	7.12	7.88	8.79	7.72
$\mathbf{L_{m\,10}}$, $\mathbf{10^6}$	Eq.6	**2.07**	**2.98**	**3.50**	**3.97**

There are some differences in load ratings and fatigue load limit, because actual bearing designs, based on the expertise of the manufacturer can deviate from standard reference geometrics, as well as used steel of specific quality. Consequently, there are differences in estimated basic and modified service life. This numerical example showed that there are no large deviations in the calculation procedures proposed by the bearing manufacturers in relation to the standard recommendations. Even more, there is only a slight difference in the results of the bearing life assessment from different manufacturers of the same rank and product quality in the bearing market.

5. ISO/TS 16281:2008

The last version of International Standard on rolling bearings dynamic load ratings and rating life was issued in 2007. In this edition, recommended calculation method for rolling bearing service life takes into account influences of reliability, lubrication, contamination, internal stresses from mounting, hardening, and the fatigue load limit of the material. It is, therefore, possible to determine bearing service life in a more complete way than before. However, the calculation method given in ISO 281:2007 do not consider the objectively present influence of internal clearance and rings tilting or misalignment on bearing service life. For this purpose, the document ISO/Technical Specification 16281, issued in 2008, describes an advanced calculation method, which covers influencing parameters additional to those described in ISO 281: tilting or misalignment, operating clearance of the bearing and internal load distribution on rolling elements. The Technical specification [10] is applied to radial ball bearing, subjected to radial and axial load and roller bearings subjected to pure radial load, both with radial clearance, edge stress and tilt. However, this document does not consider a radial ball bearing with radial clearance subjected to pure radial load, which is a common case in bearing arrangements. The proposed calculation method is not complete and cannot be applied by the user of this Technical Specification. Thereby some quantities in the proposed mathematical model can be solved only by iteration, using computer support. Regardless of this, it is significant information for the user that these influences exist and should not be negligible, as well as it is a theoretical background and basis for further development of calculation procedure considering new influences. Even more, it is stated in the Scope of [10] that it is primarily intended to be used for computer programs and that only together with ISO 281 covers the information needed for life calculations. It is recommended that either this Technical Specification or advanced computer calculations provided by bearing manufacturers, for determining the dynamic equivalent reference load under different loading condition, be used.

6. Conclusion

From 1962 to 2008, a major step was made in bearing service life calculation, by introduction modification factors. The influence of reliability other than 90%, lubrication, contamination and fatigue load limit is very well covered, which is confirmed by significant values of these factors. The influences of load distribution, internal clearance and misalignment on bearing service life has also been identified but has not been quantified through any additional life modification factors. The Technical Committee for rolling bearings is supposed to be very active and surely we could expect in next version of ISO 281 that standard formula for the rating life will be modified by additional factors for the all newly identified impacts.

7. References

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