TECHNICAL REPORT

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Rolling bearings — Explanatory notes on ISO 281 —

Part 2:
Modified rating life calculation, based on a systems approach to fatigue stresses

Roulements — Notes explicatives sur l'ISO 281 —

Partie 2: Calcul modifié de la durée nominale de base fondé sur une approche système du travail de fatigue

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 1281-2 was prepared by Technical Committee ISO/TC 4, *Rolling bearings*, Subcommittee SC 8, *Load ratings and life*.

This first edition of ISO/TR 1281-2, together with the first edition of ISO/TR 1281-1, cancels and replaces the first edition of ISO/TR 8646:1985, which has been technically revised.

ISO/TR 1281 consists of the following parts, under the general title *Rolling bearings — Explanatory notes on ISO 281*:

— *Part 1: Basic dynamic load rating and basic rating life*

— *Part 2: Modified rating life calculation, based on a systems approach of fatigue stresses*

Introduction

Since the publication of ISO 281:1990 [25], more knowledge has been gained regarding the influence on bearing life of contamination, lubrication, fatigue load limit of the material, internal stresses from mounting, stresses from hardening, etc. It is therefore now possible to take into consideration factors influencing the fatigue load in a more complete way.

Practical implementation of this was first presented in ISO 281:1990/Amd.2:2000, which specified how new additional knowledge could be put into practice in a consistent way in the life equation. The disadvantage was, however, that the influence of contamination and lubrication was presented only in a general fashion. ISO 281:2007 incorporates this amendment, and specifies a practical method of considering the influence on bearing life of lubrication condition, contaminated lubricant and fatigue load of bearing material.

In this part of ISO/TR 1281, background information used in the preparation of ISO 281:2007 is assembled for the information of its users, and to ensure its availability when ISO 281 is revised.

For many years the use of basic rating life, L_{10}, as a criterion of bearing performance has proved satisfactory. This life is associated with 90 % reliability, with commonly used high quality material, good manufacturing quality, and with conventional operating conditions.

However, for many applications, it has become desirable to calculate the life for a different level of reliability and/or for a more accurate life calculation under specified lubrication and contamination conditions. With modern high quality bearing steel, it has been found that, under favourable operating conditions and below a certain Hertzian rolling element contact stress, very long bearing lives, compared with the L_{10} life, can be obtained if the fatigue limit of the bearing steel is not exceeded. On the other hand, bearing lives shorter than the L_{10} life can be obtained under unfavourable operating conditions.

A systems approach to fatigue life calculation has been used in ISO 281:2007. With such a method, the influence on the life of the system due to variation and interaction of interdependent factors is considered by referring all influences to the additional stress they give rise to in the rolling element contacts and under the contact regions.

Rolling bearings — Explanatory notes on ISO 281 —

Part 2:
Modified rating life calculation, based on a systems approach to fatigue stresses

1 Scope

ISO 281:2007 introduced a life modification factor, a_{ISO}, based on a systems approach to life calculation, in addition to the life modification factor for reliability, a_1.These factors are applied in the modified rating life equation

$$L_{n\mathrm{m}} = a_1 \, a_{\mathrm{ISO}} \, L_{10} \tag{1}$$

For a range of reliability values, a_1 is given in ISO 281:2007 as well as the method for evaluating the modification factor for systems approach, a_{ISO}. L_{10} is the basic rating life.

This part of ISO/TR 1281 gives supplementary background information regarding the derivation of a_1 and a_{ISO}.

NOTE The derivation of a_{ISO} is primarily based on theory presented in Reference [5], which also deals with the fairly complicated theoretical background of the contamination factor, e_{C}, and other factors considered when calculating a_{ISO} .

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 281:2007, *Rolling bearings — Dynamic load ratings and rating life*

ISO 11171, *Hydraulic fluid power — Calibration of automatic particle counters for liquids*

3 Symbols

Certain other symbols are defined on an *ad hoc* basis in the clause or subclause in which they are used.

A scaling constant in the derivation of the life equation

a_{ISO} life modification factor, based on a systems approach to life calculation

a_{SLF} stress-life factor in Reference [5], based on a systems approach to life calculation (same as the life modification factor a_{ISO} in ISO 281)

a_1 life modification factor for reliability

C basic dynamic load rating, in newtons

C_{u} fatigue load limit, in newtons

C_0 basic static load rating, in newtons

c exponent in the stress-life equation (in Reference [5] and ISO 281, $c = 31/3$ is used)

D_{pw} pitch diameter, in millimetres, of ball or roller set

dV elementary integration volume, in cubic millimetres

e Weibull's exponent (10/9 for ball bearings and 9/8 for roller bearings)

e_C contamination factor

F_r bearing radial load (radial component of actual bearing load), in newtons

L_n life, corresponding to n percent probability of failure, in million revolutions

L_{nm} modified rating life, in million revolutions

L_{we} effective roller length, in millimetres, applicable in the calculation of load ratings

L_{10} basic rating life, in million revolutions

N number of load cycles

n probability of failure, expressed as a percentage

P dynamic equivalent load, in newtons

P_u fatigue load limit, in newtons (same as C_u)

Q_{max} maximum load, in newtons, of a single contact

Q_u fatigue load, in newtons, of a single contact

Q_0 maximum load, in newtons, of a single contact when bearing load is C_0

S reliability (probability of survival), expressed as a percentage

s uncertainty factor

w exponent in the load-stress relationship (1/3 for ball bearings and 1/2,5 for roller bearings)

x contamination particle size, in micrometres, with ISO 11171 calibration

Z number of rolling elements per row

α nominal contact angle, in degrees

β_{cc} lubricant cleanliness degree (in Reference [5] and Clause 5)

$\beta_{x(c)}$ filtration ratio at contamination particle size x (see symbol x above)

NOTE The designation (c) signifies that the particle counters — of particles of size x µm — shall be an APC (automatic optical single-particle counter) calibrated in accordance with ISO 11171.

η_b lubrication factor

η_c contamination factor (same as the contamination factor e_C in ISO 281)

κ viscosity ratio, ν/ν_1

Λ ratio of oil film thickness to composite surface roughness

ν actual kinematic viscosity, in square millimetres per second, at the operating temperature

ν_1 reference kinematic viscosity, in square millimetres per second, required to obtain adequate lubrication

τ_i fatigue stress criterion of an elementary volume, dV, in megapascals

τ_u fatigue stress limit in shear, in megapascals

4 Life modification factor for reliability, a_1

4.1 General

In the context of bearing life for a group of apparently identical rolling bearings, operating under the same conditions, reliability is defined as the percentage of the group that is expected to attain or exceed a specified life.

The reliability of an individual rolling bearing is the probability that the bearing will attain or exceed a specified life. Reliability can thus be expressed as the probability of survival. If this probability is expressed as S %, then the probability of failure is $(100 - S)$ %.

The bearing life can be calculated for different probability of failure levels with the aid of the life modification factor for reliability, a_1.

4.2 Derivation of the life modification factor for reliability

4.2.1 Two parameter Weibull relationship

Endurance tests, which normally involve batches of 10 to 30 bearings with a sufficient number of failed bearings, can be satisfactorily summarized and described using a two parameter Weibull distribution, which can be expressed

$$L_n = \eta \left[\ln \left(\frac{100}{S} \right) \right]^{1/e} \tag{2}$$

$$n = 100 - S \tag{3}$$

where

S is the probability, expressed as a percentage, of survival;

n is the probability, expressed as a percentage, of failure;

e is the Weibull exponent (set at 1,5 when $n < 10$);

η characteristic life.

With the life L_{10} (corresponding to 10 % probability of failure or 90 % probability of survival) used as the reference, L_n / L_{10} can be written, with the aid of Equation (2), as

$$L_n = L_{10} \left[\frac{\ln(100/S)}{\ln(100/90)} \right]^{1/e} \tag{4}$$

By including the life modification factor for reliability, a_1, Equation (4) can be written

$$L_n = a_1 L_{10} \tag{5}$$

The life modification factor for reliability, a_1, is then given by

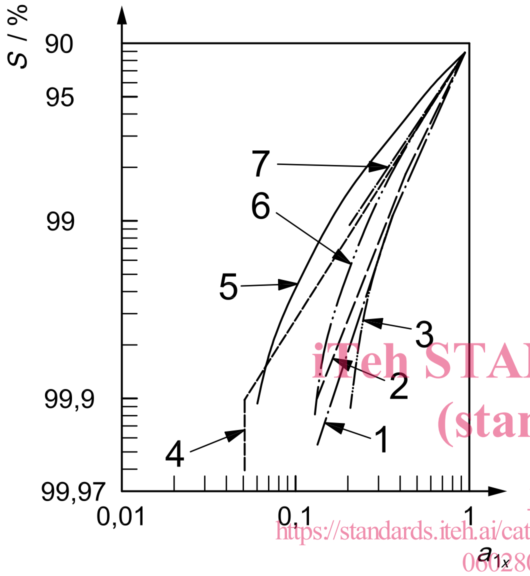
$$a_1 = \left[\frac{\ln(100/S)}{\ln(100/90)} \right]^{1/e} \tag{6}$$

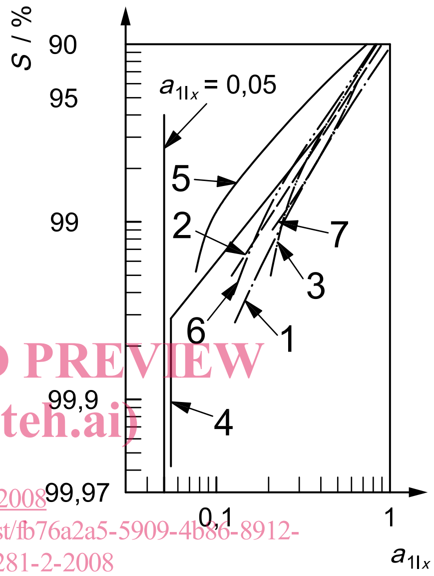
4.2.2 Experimental study of the life modification factor for reliability

References [6], [7], and [8] confirm that the two parameter Weibull distribution is valid for reliabilities up to 90 %. However, for reliabilities above 90%, test results indicate that Equation (6) is not accurate enough.

Figures 1 and 2 are reproduced from Reference [8] and illustrate a summary of the test results from References [6] to [8] and others. In Figure 1, the test results, represented by a reliability factor designated a_{1x}, are summarized. The curves are calculated as mean values of the test results. In Figure 2, a_{1lx} represents the lower value of the ($\pm 3\sigma$) range confidence limits of reliability of the test results, where σ is the standard deviation.

Figure 1 indicates that all mean value curves have a_{1x} values above 0,05, and Figure 2 confirms that the asymptotic value $a_1 = a_{1lx} = 0{,}05$ for the life modification factor for reliability is on the safe side.





Key

a_{1x} reliability factor
S reliability

1 Reference [8] (total)
2 Reference [8] (ball bearings)
3 Reference [8] (roller bearings)
4 Reference [6]
5 Reference [7]
6 Okamoto et al.
7 ISO 281

Figure 1 — Factor a_{1x}

Reproduced, with permission, from Reference [8]

Key

a_{1lx} lower limit of the $\pm 3\sigma$ confidence range for reliability
S reliability

1 Reference [8] (total)
2 Reference [8] (ball bearings)
3 Reference [8] (roller bearings)
4 Reference [6]
5 Reference [7]
6 Okamoto et al.
7 ISO 281

Figure 2 — Factor a_{1lx}

Reproduced, with permission, from Reference [8]

4.2.3 Three parameter Weibull relationship

The tests (4.2.2) indicate that a three parameter Weibull distribution would better represent the probability of survival for values > 90 %.

The three parameter Weibull relationship is expressed by

$$L_n - \gamma = \eta \left[\ln\left(\frac{100}{S}\right) \right]^{1/e} \tag{7}$$

where γ is the third Weibull parameter.

By introducing a factor C_γ to define γ as a function of L_{10}, γ can be written

$$\gamma = C_\gamma L_{10} \tag{8}$$

$$L_n - C_\gamma L_{10} = \left(L_{10} - C_\gamma L_{10}\right) \left[\frac{\ln(100/S)}{\ln(100/90)} \right]^{1/e} \tag{9}$$

$$L_n = a_1 L_{10} \tag{10}$$

with the new life modification factor for reliability, a_1, defined as

$$a_1 = \left(1 - C_\gamma\right) \left[\frac{\ln(100/S)}{\ln(100/90)} \right]^{1/e} + C_\gamma \tag{11}$$

The factor C_γ represents the asymptotic value of a_1 in Figure 2, i.e. 0,05. This value and a selected Weibull slope, $e = 1{,}5$, give a good representation of the curves in Figure 2. With these values inserted in Equation (11), the equation for the life modification factor for reliability can be written

$$a_1 = 0{,}95 \left[\frac{\ln(100/S)}{\ln(100/90)} \right]^{2/3} + 0{,}05 \tag{12}$$

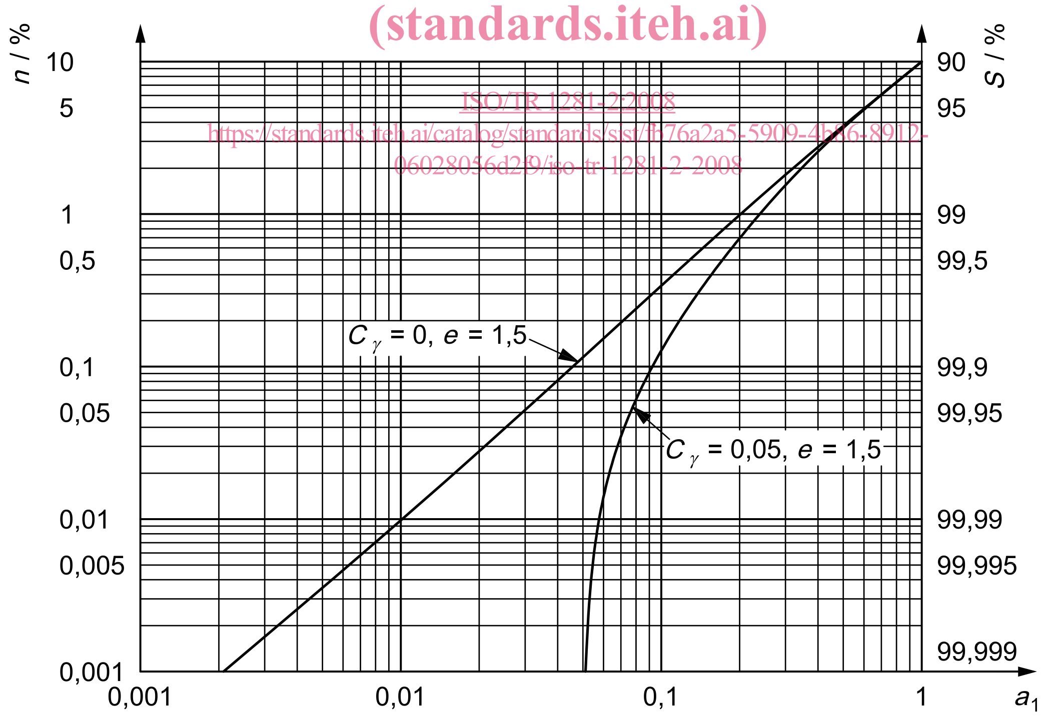
Table 1 lists reliability factors calculated by Equation (11) for $C_\gamma = 0$ and $e = 1{,}5$, and by Equation (12), along with the life adjustment factor for reliability, a_1, in ISO 281:1990 [25]. The calculations are made for reliabilities, S, from 90 % to 99,95 %.

Values of a_1 calculated by Equation (12) are adopted in ISO 281:2007.

Table 1 — The life modification factor for reliability, a_1, for different Weibull distributions

Reliability S %	Reliability factor a_1 ISO 281:1990 [25]	 $C_\gamma = 0$ $e = 1{,}5$	 $C_\gamma = 0{,}05$ $e = 1{,}5$
90	1	1	1
95	0,62	0,62	0,64
96	0,53	0,53	0,55
97	0,44	0,44	0,47
98	0,33	0,33	0,37
99	0,21	0,21	0,25
99,5	—	0,13	0,17
99,9	—	0,04	0,09
99,95	—	0,03	0,08

Figure 3 shows the probability of failure and the probability of survival as functions of the life modification factor for reliability, a_1, by means of one curve for $C_\gamma = 0$ and $e = 1{,}5$ and one curve for $C_\gamma = 0{,}05$ and $e = 1{,}5$.



Key

a_1 life modification factor for reliability
C_γ asymptotic value of a_1
e Weibull exponent
n probability of failure
S probability of survival ($S = 100 - n$)

Figure 3 — Weibull distributions with $C_\gamma = 0$ and $C_\gamma = 0{,}05$

5 Background to the life modification factor, a_{ISO}

5.1 General

The derivation of the life modification factor, a_{ISO}, in ISO 281 is described in Reference [5], where the same factor is called stress-life factor and designated a_{SLF}. In this part of ISO/TR 1281, further information of the derivation of the factor a_{SLF} is given, based on Reference [22].

According to Reference [5], Section 3.2, based on the conditions valid for ISO 281 (i.e. the macro-scale factor $\eta_{\text{a}} = 1$ and $A = 0{,}1$), the equation for a_{SLF} can be written

$$a_{\text{SLF}} = 0{,}1 \left\langle 1 - \left(\eta_{\text{b}} \, \eta_{\text{c}} \frac{P_{\text{u}}}{P} \right)^{w} \right\rangle^{-c/e} \qquad (13)$$

The background to the lubrication factor, η_{b}, and the contamination factor, η_{c}, is explained in 5.2 and 5.3 respectively. The contamination factor, η_{c}, corresponds to the factor e_{C} in ISO 281.

5.2 The lubrication factor, η_{b}

This subclause covers the relationship between the lubrication quality, which is characterized by the viscosity ratio, κ, in ISO 281, and its influence on the fatigue stress.

For this purpose, the fatigue life reduction resulting from an actual rolling bearing (with standard raceway surface roughness) compared with one characterized by an ideally smooth contact, as from purely Hertzian, friction-free, stress distribution hypothesis, needs to be quantified.

This can be done by comparing the theoretical fatigue life between a real bearing (with standard raceway surface roughness) and the fatigue life of a hypothetical bearing with ideally smooth and friction-free contacting surfaces. Thus the life ratio of Equation (14) has to be quantified

$$\frac{L_{10,\text{rough}}}{L_{10,\text{smooth}}} = \frac{a_{\text{SLF,rough}}}{a_{\text{SLF,smooth}}} \qquad (14)$$

with $(C/P)^{p}$ constant in the life equation. The ratio in Equation (14) can be evaluated numerically using the Ioannides-Harris fatigue life stress integral of Equation (15) (see Reference [21]):

$$\ln \frac{100}{S} \approx A N^{e} \int_{V_{\text{R}}} \frac{\langle \tau_i - \tau_{\text{u}} \rangle^{c}}{z'^{h}} \text{d}V \qquad (15)$$

where

- h is a depth exponent;
- z' is a stress-weighted average depth;
- τ represents stress criteria.

In Equation (15), the relevant quantity affecting the life ratio in Equation (14) is the volume-related stress integral I, which can be expressed

$$I = \int_{V_{\text{R}}} \frac{\langle \tau_i - \tau_{\text{u}} \rangle^{c}}{z'^{h}} \text{d}V \qquad (16)$$

By means of Equations (15) and (16), the life equation can be written

$$L_{10} = 10^{-6} N u^{-1} \approx \left(\frac{\ln(100/90)}{A\, I} \right)^{1/e} u^{-1} \tag{17}$$

The basic rating life in number of revolutions in Equation (17) is expressed as the number of load cycles obtained with 90 % probability, N, divided by the number of over-rolling per revolution, u.

In Equation (17), the stress integral, I, can be computed for both standard roughness and for an ideally smooth contact, and it can be used for estimation of the expected effect of raceway surface roughness on bearing life with the aid of Equations (14) and (17). The following derivation then applies

$$\left(\frac{L_{10,\text{rough}}}{L_{10,\text{smooth}}} \right)_{(m,n)} = \left(\frac{I_{\text{smooth}}}{I_{\text{rough}}} \right)_{(m,n)}^{1/e} = \left(\frac{a_{\text{SLF,rough}}}{a_{\text{SLF,smooth}}} \right)_{(m,n)} \tag{18}$$

In general, this ratio depends on the surface topography (index m) and amount of surface separation or amount of interposed lubricant film (index n).

The lubrication factor can now be directly derived from Equation (18) by introducing the stress-life factor according to Equation (13). For standard-bearing roughness and under the hypothesis of an ideally clean lubricant represented by setting the factor $\eta_c = 1$, the stress-life factor can be written

$$a_{\text{SLF,rough}} = 0{,}1 \left\langle 1 - \left(\eta_b \frac{P_u}{P} \right)^{w} \right\rangle^{-c/e} \tag{19}$$

Similarly, in the case of a well lubricated, hypothetical bearing with ideally smooth surfaces, $\kappa \geqslant 4$, and $\eta_b = 1$ according to the definition of the ranges of η_b in Reference [5]. Equation (19) can then be written

$$a_{\text{SLF,smooth}} = 0{,}1 \left\langle 1 - \left(\frac{P_u}{P} \right)^{w} \right\rangle^{-c/e} \tag{20}$$

By inserting Equations (19) and (20) into Equation (18), the following equation is derived

$$\eta_{b(m,n)} = \frac{P}{P_u} \left\langle 1 - \left\langle 1 - \left(\frac{P_u}{P} \right)^{w} \right\rangle \left(\frac{I_{\text{smooth}}}{I_{\text{rough}}} \right)_{(m,n)}^{-1/c} \right\rangle^{1/w} \tag{21}$$

Equation (21) shows that a ($m \times n$) matrix of numerically derived η_b values can be constructed, starting from the calculation of the fatigue life and related stress-volume integral of standard rough bearing raceway surfaces. This calculation has to be extended to include different amounts of surface separation (oil film thickness), from thin films up to full separation in the rolling element/raceway contact.

The following steps were used for the numerical derivation of the $\eta_{b(m,n)}$, considering actual rolling bearing surfaces.

1) Surface mapping of a variety of rolling bearing surfaces using optical profilometry.

2) Calculation of the operating conditions for the heaviest loaded contact of the bearing.

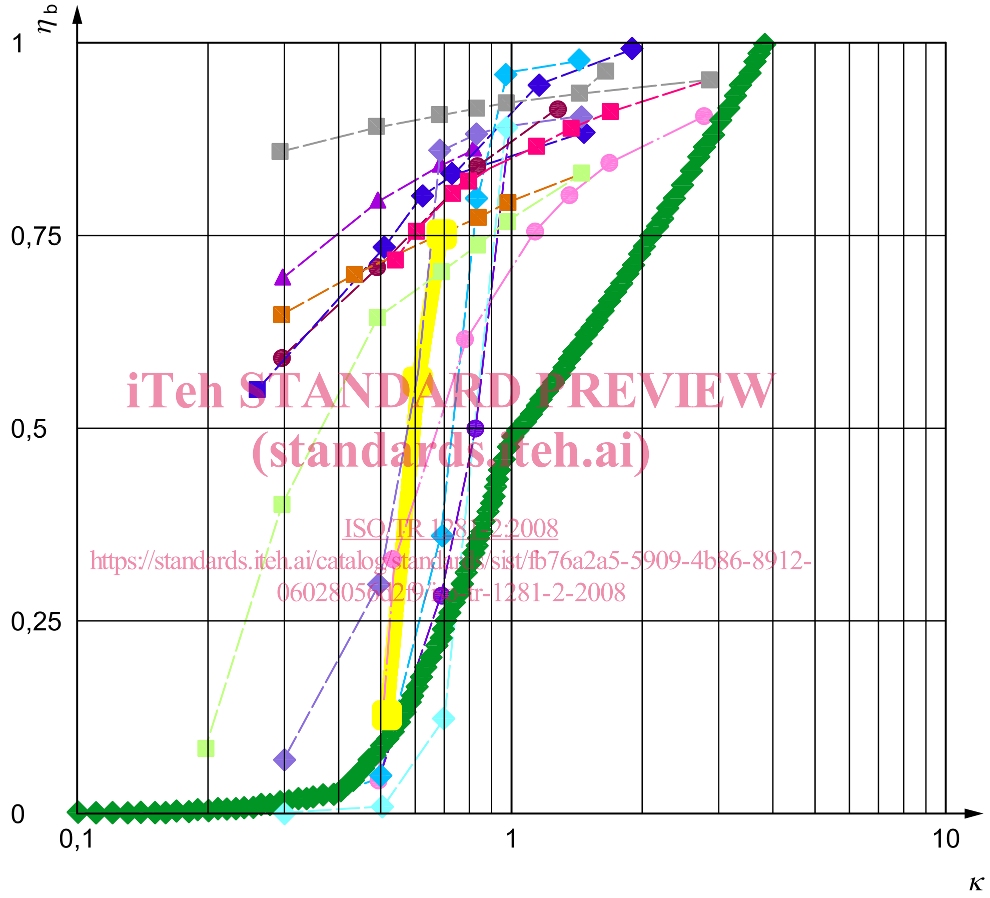
3) Calculation of the pressure fluctuations resulting from the surface topography, lubrication conditions and resulting elastic deformation by means of the FFT (fast Fourier transform) method.

4) Calculation of the smooth Hertzian stress integral of the contacts using Equation (16).

5) Superimposition of the smooth Hertzian pressure to calculate internal stresses and assessment of the fatigue stress integral of the actual rough contact using Equation (16).

6) Calculation of η_b from Equation (21) in relation to reference operating conditions and resulting viscosity ratio, κ, of the bearing.

Following the methods described above, a set of $\eta_{b(m,\ n)}$ values was constructed. The resulting plots of κ against η_b and interpolation curves are shown in Figure 4. For clarity, only a representative group of standard-bearing raceway surfaces are presented. The generated $\eta_{b(m,\ n)}$ curves show a typical trend with a rapid decline of η_b for a reduction of the nominal lubrication conditions, κ, of the contact.



Key

η_b lubrication factor

κ viscosity ratio

Figure 4 — Summary of the numerically calculated lubrication factors for different surface roughness samples compared with the lubrication factor used in ISO 281 (thick line)

In Figure 4, the numerically calculated lubrication factors for different surface roughnesses are indicated and, for comparison, that used in ISO 281, represented by the thick line. The general form of the equation of this thick line is

$$\eta_b(\kappa)_{nom} = \eta_b \frac{(\kappa)_{brg}}{(\psi)_{brg}} = \left(3{,}387 - \frac{b_1(\kappa)}{\kappa^{b_2(\kappa)}}\right)^{5/2} \qquad (22)$$