Chapter 6: Rolling Bearings

Bearings

In the context of a machine or structure, the word *bearing* refers to contacting surfaces through which load is transmitted.

Bearings are machine elements that allow relative motion between two parts while transmitting forces from one part to the other.

Bearing classification

Bearings may be broadly classified as:

→ Rolling element (antifriction) bearings

→ Plain (sliding) bearings

In contrast to the sliding interface in plain bearings, for rolling element bearings the rotating shaft is separated from the fixed frame by interposed rolling elements

➥ thus rolling friction replaces sliding friction.

Rolling Bearings

The terms *rolling element bearing*, *rolling bearing*, *rolling-contact bearing*, and *antifriction bearing* are synonymous.

Main load is transferred through elements in rolling contact rather than in sliding contact.

The term “antifriction” does NOT mean the absence of friction. It’s just that the amount of friction is very small.

Rolling Bearings

Rolling bearings support and guide, with minimal friction, rotating or oscillating machine elements – such as shafts, axles or wheels – and transfer loads between machine components. Rolling bearings provide high precision and low friction and therefore enable high rotational speeds while reducing noise, heat, energy consumption and wear. They are cost-effective and exchangeable machine elements that typically follow national or international dimension standards.[1]

[1] From SKF handbook

Design → Selection

An extremely wide variety of rolling bearings have already been designed, and are produced by various bearing manufacturers.

Among all the machine elements, rolling bearings have received the greatest amount of refinement, engineering care, statistical testing, and precision in production.

From the point of view of the mechanical designer, "design" means given a situation, **selecting** a suitable bearing from the wide variety already available.

True *design* is done only by the specialized designer working in the bearing industry.

Bearing Manufacturers

Some top global bearing manufacturers are:

- SKF (Sweden)
- Schaeffler (Germany) - Brands: FAG, INA, LuK
- NSK (Japan)
- NTN (Japan)
- JTEKT (Japan)
- Timken (USA) - leader in tapered roller bearings
- Nachi-Fujikoshi (Japan)
- ZWZ (China) - China's oldest and largest
- C&U (China)
- MinebeaMitsumi (Japan) - leader in miniature bearings

Some of these companies have plants in India too.
Tata Bearings has a plant at Kharagpur.

Bearing Components

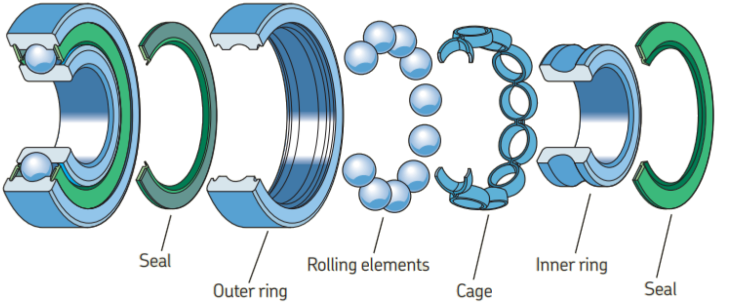
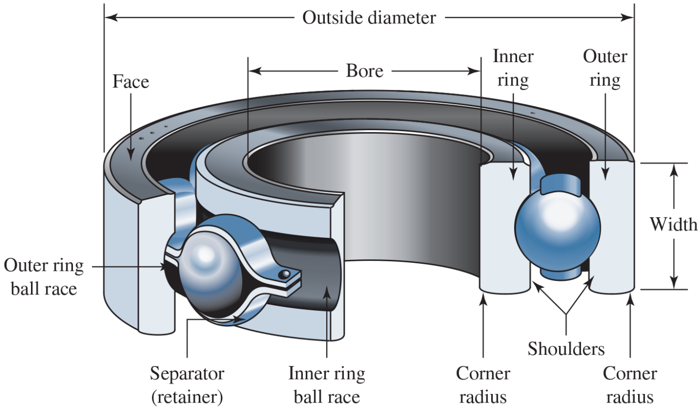


Figure from SKF handbook

Here, the rolling elements shown are balls. But they could be rollers also. Rollers, in turn, can be of various kinds (to be discussed later).

Nomenclature of a bearing



Classification of Bearings

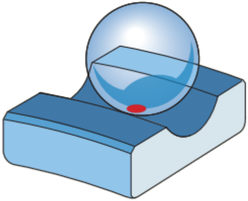
Based on rolling element type

Based on the type of rolling elements used, rolling bearings can be classified as:

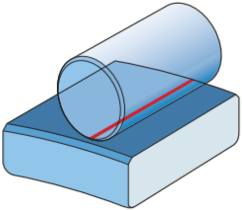
- Ball bearings
- Roller bearings - these, in turn, can be of different types

Note: Roller bearings are a subset of rolling bearings. All roller bearings are rolling bearings. But all rolling bearings are not roller bearings. (I didn't come up with this terminology!)

Nature of contact and stresses[2]



Balls make point contact with the ring raceways. With increasing load acting on the bearing, the contact point becomes an elliptical area. The small contact area provides low rolling friction, which enables ball bearings to accommodate high speeds but also limits their load-carrying capacity.



Rollers make line contact with the ring raceways. With increasing load acting on the bearing, the contact line becomes somewhat rectangular in shape. Because of the larger contact area and the consequently higher friction, a roller bearing can accommodate heavier loads, but lower speeds, than a same-sized ball bearing.

[2] From SKF handbook

A small digressing note

Note that the different kinds of contacts and stresses generated between the rolling elements and races are a big motivating application of an entire branch of advanced mechanics of solids called **contact mechanics.**

Contact mechanics is a highly mathematical area of study. It includes famous classical problems like the Flamant problem, Boussinesq problem, Hertzian contact - leading to more advanced and modern frameworks, and is a highly active area of research that encompasses various scientific considerations beyond just mechanical ones.

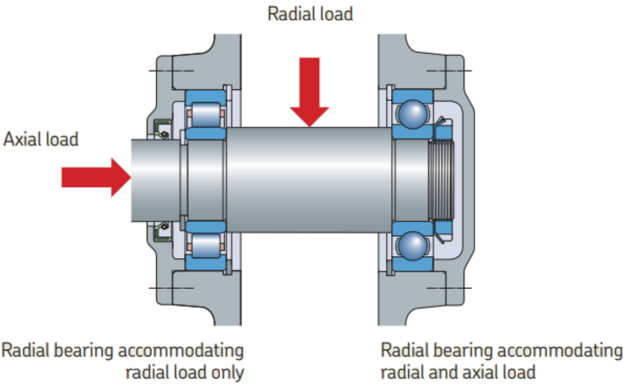
Classification of Bearings

Based on loading direction

Based on the direction of the load they accommodate, rolling bearings are classified into:

- Radial bearings
- Thrust bearings

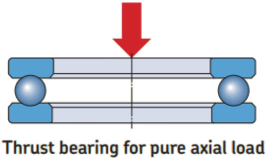
Radial Bearings

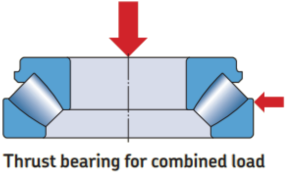


Radial bearings accommodate loads that are predominantly perpendicular to the shaft. Some radial bearings can support only pure radial loads, while most can additionally accommodate some axial loads in one direction and, in some cases, both directions.

Source: SKF Handbook

Thrust Bearings

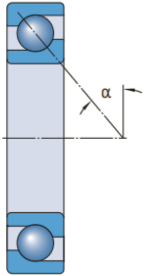




Thrust bearings accommodate loads that act predominantly along the axis of the shaft. Depending on their design, thrust bearings may support pure axial loads in one or both directions, and some can additionally accommodate radial loads (combined loads). Thrust bearings cannot accommodate speeds as high as same-sized radial bearings.

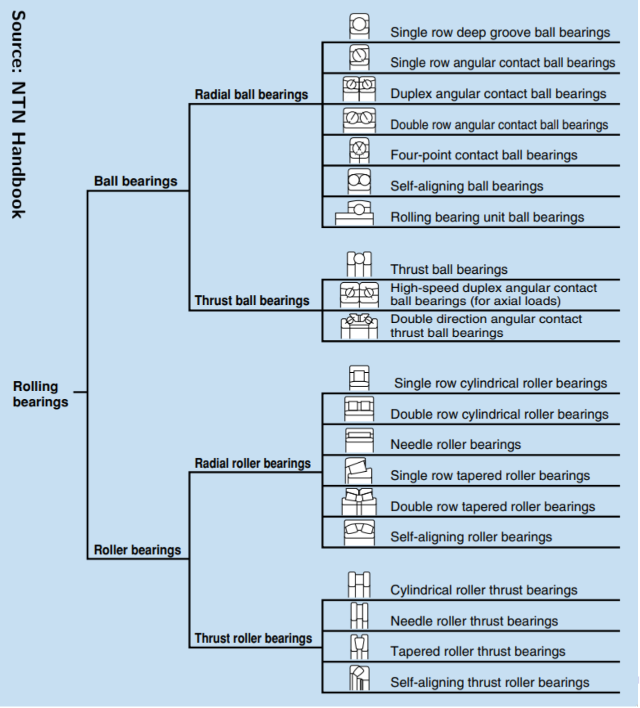
Source: SKF Handbook

Contact Angle



The contact angle determines which group the bearing belongs to. Bearings with a contact angle $\leq 45^\circ$ are radial bearings, the others are thrust bearings.

Source: SKF Handbook


Source: NTN Handbook
Rolling bearings
Ball bearings
Radial ball bearings
Single row deep groove ball bearings
Single row angular contact ball bearings
Duplex angular contact ball bearings
Double row angular contact ball bearings
Four-point contact ball bearings
Self-aligning ball bearings
Rolling bearing unit ball bearings
Thrust ball bearings
Thrust ball bearings
High-speed duplex angular contact ball bearings (for axial loads)
Double direction angular contact thrust ball bearings
Roller bearings
Radial roller bearings
Single row cylindrical roller bearings
Double row cylindrical roller bearings
Needle roller bearings
Single row tapered roller bearings
Double row tapered roller bearings
Self-aligning roller bearings
Thrust roller bearings
Cylindrical roller thrust bearings
Needle roller thrust bearings
Tapered roller thrust bearings
Self-aligning thrust roller bearings

Deep Groove Ball Bearing

Single Row

Double Row

Source: SKF

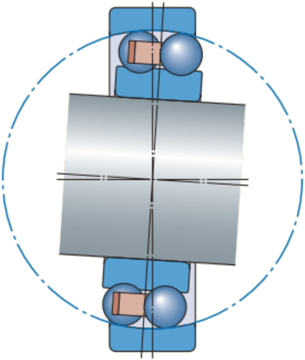
Angular Contact Ball Bearing

Single Row

Double Row

Source: SKF

Self-Aligning Ball Bearing



Self-aligning ball bearing accommodates misalignment

Source: SKF

Thrust Ball Bearing

Single direction

Double direction

Source: SKF

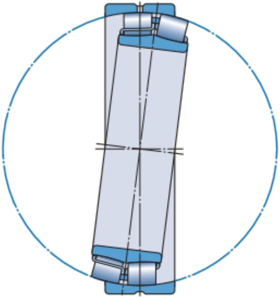
Cylindrical Roller Bearing

Single Row

Double Row

Source: SKF

Spherical Roller Bearing



Self-aligning property of the bearing

Source: SKF

Bearing Life Definitions

If a bearing is clean and properly lubricated, is mounted and sealed against the entrance of dust and dirt, is maintained in this condition, and is operated at reasonable temperatures, then metal fatigue will be the only cause of failure.

Bearing failure: Spalling or pitting of the load-carrying surfaces.
Timken company: Spalling or pitting of an area of 0.01 in^2.

Bearing Life: The life measure of an individual bearing is the total number of revolutions or hours at constant speed of bearing operation until the failure criterion is developed.

However, *bearing life* is a stochastic variable. It has a distribution and associated statistical parameters.

Bearing Life Definitions

Rating Life:

- Applies to a group of nominally identical ball or roller bearings.
- No. of revolutions (or hours at constant speed) that 90 percent of a group of bearings will achieve or exceed before the failure criterion develops.
- It is the 10th percentile location of the bearing group's revolutions-to-failure distribution.
- Also called minimum life, L_{10} life, and B_{10} life.

Median Life:

- 50th percentile life of a group of bearings.
- Sometimes the term average life is also used (even though average $\neq$ median)
- Median life is between 4 and 5 times the L_{10} life.

Load Rating Definitions

Catalog Load Rating, C_{10}:
Constant radial load that causes 10% of a group of bearings to failure at the bearing manufacturer's rating life.

Basic Dynamic Load Rating or Basic Load Rating:
If the manufacturer's rating life is 10^6 revolutions, then the catalog load rating is referred to as the Basic Dynamic Load Rating or Basic Load Rating.

Load Rating Definitions

Basic Static Load Rating, C_0**:**
It is the load that will produce a total permanent deformation in the race and rolling element at any contact point of 0.0001 times the diameter of the rolling element.

It is used in combining radial and thrust loads into an equivalent radial load (to be discussed later).

Load-Life Relationship

Nominally identical groups of bearings are tested to the life-failure criterion at different loads.

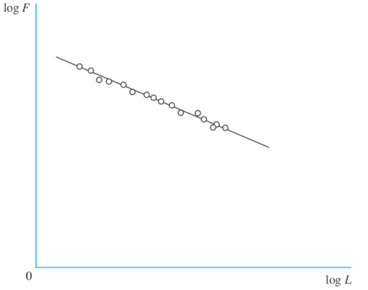
A plot of load vs life on log-log scale is approximately linear.

Using a regression equation to represent the line:

$$FL^{1/a} = \text{constant}$$

- $a = 3$ for ball bearings
- $a = 10/3$ for roller bearings (cylindrical and tapered roller)

Units of L: No. of revolutions



Load-Life Relationship

Applying the load-life relationship to two different conditions:

$$F_1 L_1^{1/a} = F_2 L_2^{1/a}$$

If the life is expressed in hours at a given speed, then:

$$L = 60 \mathscr{L} n$$

where $\mathscr{L}$ is in hours, n is in rev/min, and the factor 60 is in min/h. (Remember: L is no. of revolutions)

Reliability-Life Relationship

Define the life measure in dimensionless form as $x = L/L_{10}$. Then the reliability is expressed with a Weibull distribution as:

$$R = \exp\left[-\left(\frac{x - x_0}{\theta - x_0}\right)^b\right]$$

x : life measure dimensionless variable, L/L_{10}

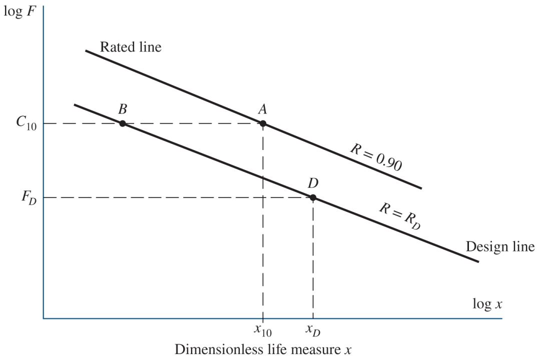
x_0 : guaranteed or "minimum" value of x

θ : characteristic parameter. For rolling bearings, this corresponds to the 63.2121 percentile value of x

b : shape parameter that controls the skewness. For rolling bearings, $b \approx 1.5$

Relating Load, Life, and Reliability

- Catalog information is at point A, at coordinates C_{10} and $x_{10} = L_{10}/L_{10} = 1$, on the 0.90 reliability contour.
- Design information is at point D, at coordinates F_D and x_D, on the $R = R_D$ reliability contour.
- The designer must move from point D to point A via point B.

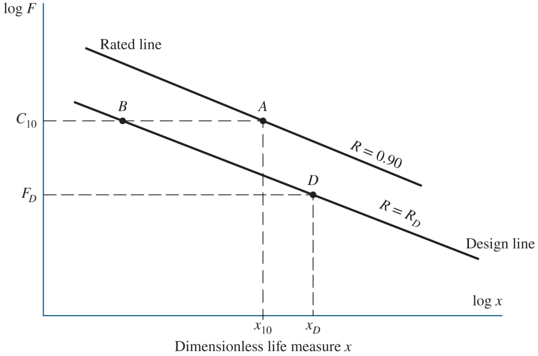


Relating Load, Life, and Reliability

Along a constant reliability contour (BD), we have:

$$F_B x_B^{1/a} = F_D x_D^{1/a},$$

$$\text{or,} \quad F_B = F_D \left(\frac{x_D}{x_B} \right)^{1/a}$$



Relating Load, Life, and Reliability

$$R_B = R_D = \exp\left[-\left(\frac{x_B - x_0}{\theta - x_0}\right)^b\right]$$

Then, solving for x_B, we obtain:

$$x_B = x_0 + (\theta - x_0)\left(\ln\frac{1}{R_D}\right)^{1/b}$$

Substituting x_B in the expression of F_B (previous slide), we have:

$$F_B = F_D\left(\frac{x_D}{x_B}\right)^{1/a} = F_D\left[\frac{x_D}{x_0 + (\theta - x_0)[\ln(1/R_D)]^{1/b}}\right]^{1/a}$$

This F_B is nothing but $F_A = C_{10}$, along the constant load line (AB). Sometimes, an application factor, a_f is placed in front of F_D. This a_f acts as a "factor of safety" to increase the design load to account for overload, dynamic loading, and uncertainty.

Relating Load, Life, and Reliability

For the special case when $R_D = 0.90$ itself, we have the denominator:

$$x_0 + (\theta - x_0)[\ln(1/R_D)]^{1/b} \approx 1.$$

Thus, the F_B expression reduces to $C_{10} = F_D \left(\frac{L_D}{L_{10}}\right)^{1/a}$.

Note also, that: $\ln(1/R_D) = -\ln R_D \approx 1 - R_D$ (true for $R_D \geq 0.90$, i.e. for small values of $1 - R_D$). Thus, we have:

$$C_{10} = F_D \left[\frac{x_D}{x_0 + (\theta - x_0)(1 - R_D)^{1/b}}\right]^{1/a}$$

Weibull Parameters

The Weibull parameters x_0, θ, and b are usually provided by the catalog.

Typical values from two manufacturers are provided in the table below:

		Weibull Parameters Rating Lives		
Manufacturer	**Rating Life, Revolutions**	x_0	θ	b
1	$90(10^6)$	0	4.48	1.5
2	$1(10^6)$	0.02	4.459	1.483

Verify for yourself that when $R_D = 0.90$:
$x_0 + (\theta - x_0)[\ln(1/R_D)]^{1/b} \approx 1$ for the above values.

An Alternate Way of Handling Reliability

Instead of explicitly going through the Weibull distribution route, we can use an alternate route to handle different reliabilities:
➥ The alternate route is to use a **reliability adjustment factor**.

The reliability adjustment factor can be expressed either as a load factor or as a life factor → Current practice is to use a reliability life-adjustment factor, K_R.

The bearing rating life, L_{10} corresponding to $R = 0.90$, may be adjusted to some other reliability using:

$$L_R = K_R L_{10},$$

where L_R is called the reliability-adjusted rating life.

Relating K_R to the Weibull parameters

If the expression for reliability-adjusted life using the reliability life-adjustment factor K_R is compared with the expression for x obtained from the Weibull distribution, we obtain:

$$K_R = x_0 + (\theta - x_0)\left(\ln \frac{1}{R}\right)^{1/b}$$

Compare the above with the relation used by Timken[3]:

$$K_R = 0.05 + 4.26\left(\ln \frac{1}{R}\right)^{2/3}$$

[3] Timken Engineering Manual

Reliability Life-Adjustment Factor K_R

The values of K_R at different reliabilities provided by the Timken Engineering Manual are[4]:

R (percent)	L_n	a_1
90	L_{10}	*1.00*
95	L_5	0.64
96	L_4	0.55
97	L_3	0.47
98	L_2	0.37
99	L_1	0.25
99.5	$L_{0.5}$	0.175
99.9	$L_{0.1}$	0.093

For $R = 90$ to 99%, identical values are provided by the SKF Rolling Bearings Catalogue.

[4]Both Timken and SKF name the factor as a_1 instead of K_R

Combined Reliability of Multiple Bearings

- If the combined reliability of multiple bearings on a shaft or in a gearbox is desired, then the total reliability is equal to the product of the individual reliabilities.
- For two bearings on a shaft, $R = R_A R_B$. Here, each of R_A and R_B is greater than R.
- During design, we can begin by making R_A and R_B equal to $\sqrt{R}$. If "rounding up" is done in the selection process, the total reliability will exceed the goal R.
- It is possible to to have $R_A > \sqrt{R}$ and "round down" on R_B, such that $R_A R_B$ still exceeds R.

Combined Radial and Thrust Loading

When ball bearings carry both an axial thrust load F_a and a radial load F_r, we need to use an **equivalent load** F_e.

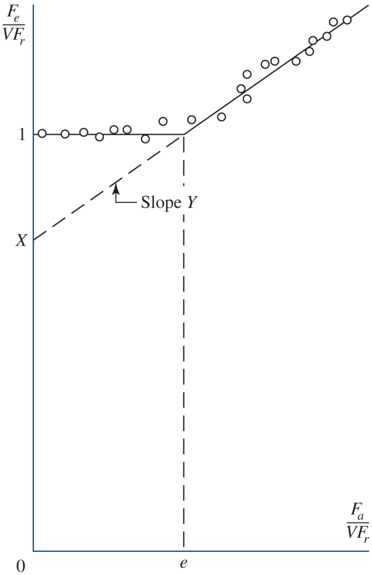
A plot of $F_e/(VF_r)$ vs $F_a/(VF_r)$

is obtained experimentally.

V is a rotation factor to account

for the difference in ball rotations for outer ring vs inner ring rotation.

- ➥ $V = 1$ for inner ring rotation
- ➥ $V = 1.2$ for outer ring rotation

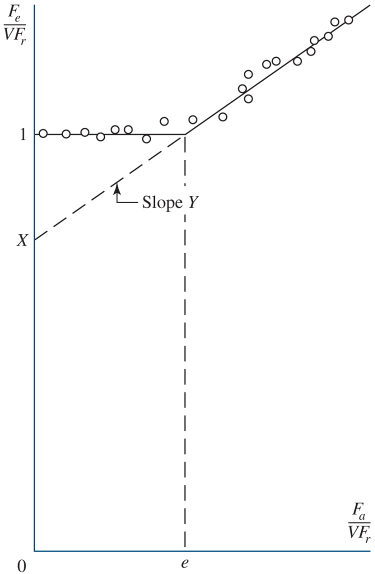


Combined Radial and Thrust Loading

The data can be approximated by two straight lines:

$$\frac{F_e}{VF_r} = 1, \quad \text{when} \quad \frac{F_a}{VF_r} \le e,$$
$$\frac{F_e}{VF_r} = X + Y\frac{F_a}{VF_r}, \quad \text{when} \quad \frac{F_a}{VF_r} > e,$$

X is the intercept on the ordinate and Y is the slope.
Basically means that F_e equals F_r for smaller ratios of F_a/F_r, then begins to rise for values of F_a/F_r larger than some value e.



Combined Radial and Thrust Loading

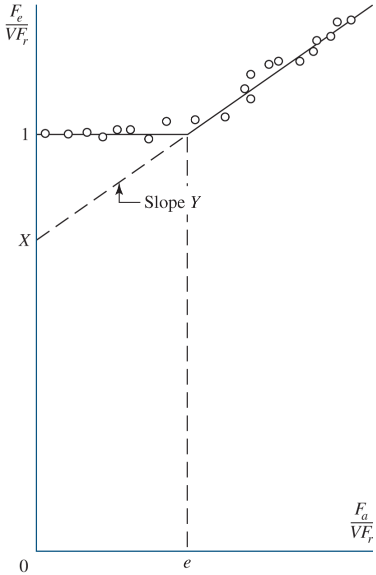
It is common to express the two equations as a single equation:

$$F_e = X_i V F_r + Y_i F_a$$

where

$$i = 1 \ \text{ when } \ F_a/(VF_r) \le e,$$
$$i = 2 \ \text{ when } \ F_a/(VF_r) > e$$

The factors X and Y depend on the geometry and construction of the specific bearing.



Equivalent Force Load Factors for Ball Bearings

F_a/C_0	e	$F_a/(VF_r) \le e$		$F_a/(VF_r) > e$	
		X_1	Y_1	X_2	Y_2
0.014*	0.19	1.00	0	0.56	2.30
0.021	0.21	1.00	0	0.56	2.15
0.028	0.22	1.00	0	0.56	1.99
0.042	0.24	1.00	0	0.56	1.85
0.056	0.26	1.00	0	0.56	1.71
0.070	0.27	1.00	0	0.56	1.63
0.084	0.28	1.00	0	0.56	1.55
0.110	0.30	1.00	0	0.56	1.45
0.17	0.34	1.00	0	0.56	1.31
0.28	0.38	1.00	0	0.56	1.15
0.42	0.42	1.00	0	0.56	1.04
0.56	0.44	1.00	0	0.56	1.00

*Use 0.014 if $F_a/C_0 < 0.014$.

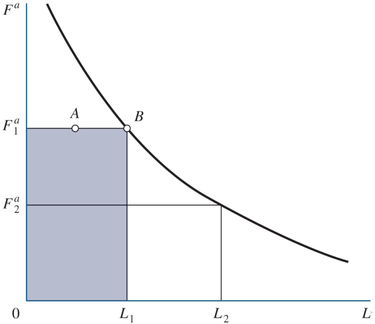
X and Y are functions of e, which is a function of F_a/C_0.
C_0 is the bastic static load rating.

Variable Loading

The load-life relationship can be rewritten as:
$F^a L = \text{constant} = K$.

For a load level of F_1, run to the failure criterion (life, L_1), the area under the $F_1 - L_1$ trace is numerically equal to K. Similarly, for $F_2 - L_2$, and so on.

The linear damage theory states that for load level F_1 run to $l_1 (< L_1)$, the damage measured will be $D_1 = F_1^a l_1$

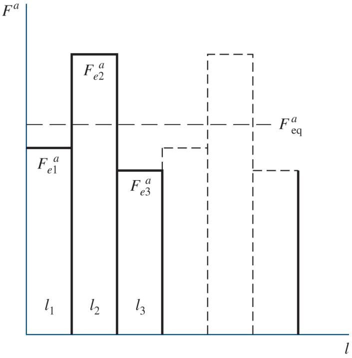


Variable Loading

Consider the piecewise continuous cycle. The loads F_{ei} are equivalent radial-thrust loads. The damage done is:

$$D = F_{e1}^a l_1 + F_{e2}^a l_2 + F_{e3}^a l_3 + \cdots$$

The equivalent steady load F_{eq} when run for $l_1 + l_2 + l_3 + \cdots$ revolutions does the same damage D:
$D = F_{\mathrm{eq}}(l_1 + l_2 + l_3 + \cdots)$. Thus:



$$F_{\mathrm{eq}} = \left[\frac{F_{e1}^a l_1 + F_{e2}^a l_2 + F_{e3}^a l_3 + \cdots}{l_1 + l_2 + l_3 + \cdots}\right]^{1/a} = \left[\sum f_i F_{ei}^a\right]^{1/a},$$

where $f_i = l_i / \sum l_i$ is the fraction of revolution run up under load F_{ei}.

Variable Loading

Note that $l_i = n_i t_i$, where n_i is the rotational speed at load F_{ei} and t_i is the duration of application of the load at that speed. Thus:

$$F_{\mathrm{eq}} = \left[\frac{\sum n_i t_i F_{ei}^a}{\sum n_i t_i} \right]^{1/a}$$

Remember that since $F^a L = \mathrm{constant} = K$, the equivalent life corresponding to F_{eq} will be: $L_{\mathrm{eq}} = \dfrac{K}{F_{\mathrm{eq}}^a}$.
In general, L_{eq} will be larger than $(l_1 + l_2 + l_3 + \cdots)$.

Variable Loading

Under the linear damage hypothesis, failure occurs when the damage D equals the constant $K = F^a L$. Thus,

$$K = F^a_{\mathrm{eq}} L_{\mathrm{eq}} = F^a_{e1} l_1 + F^a_{e2} l_2 + F^a_{e3} l_3 + \cdots ,$$

with $L_{\mathrm{eq}} = l_1 + l_2 + l_3 + \cdots$ (see the previous slide: in general, this equality does not hold)

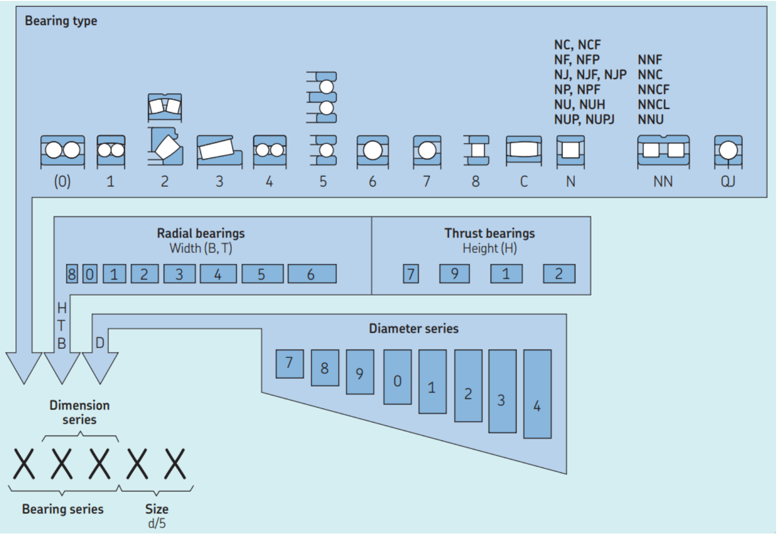
Note also that: $K = F^a_{e1} L_1 = F^a_{e2} L_2 = F^a_{e3} L_3 = \cdots$

Therefore, we can write:

$$K = F^a_{e1} l_1 + F^a_{e2} l_2 + F^a_{e3} l_3 + \cdots = \frac{K}{L_1} l_1 + \frac{K}{L_2} l_2 + \frac{K}{L_3} l_3 + \cdots = K \sum \frac{l_i}{L_i},$$

$$\text{implying} \quad \sum \frac{l_i}{L_i} = 1.$$

Bearing Designation



Source: SKF Handbook

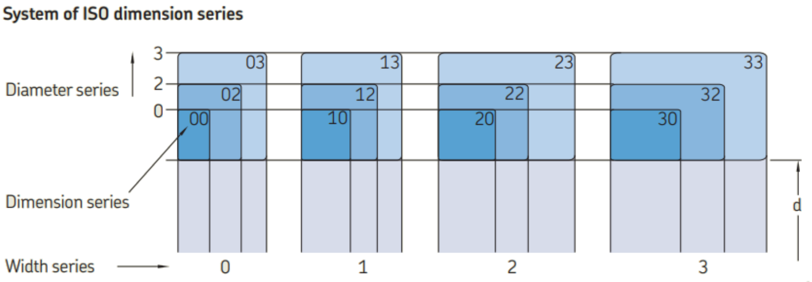
Bearing Designation

Code	Bearing type
0	Double row angular contact ball bearing
1	Self-aligning ball bearing
2	Spherical roller bearing, spherical roller thrust bearing
3	Tapered roller bearing
4	Double row deep groove ball bearing
5	Thrust ball bearing
6	Single row deep groove ball bearing
7	Single row angular contact ball bearing
8	Cylindrical roller thrust bearing
C	CARB toroidal roller bearing
N	Cylindrical roller bearing. Two or more letters are used to identify the number of the rows or the configuration of the flanges, e.g. NJ, NU, NUP, NN, NNU, NNCF
QJ	Four-point contact ball bearing
T	Tapered roller bearing in accordance with ISO 355

Source: SKF Handbook

Bearing Designation

Dimension Series



Source: This ISO system is given in the SKF Handbook; the same is given in Shigley and is referred to as the American Bearing Manufacturers' Association (ABMA) plan.

Bearing Designation
Naming system

The number and letter combinations in the basic designation have the following meangins:

- The first digit or letter or combination of letters identifies the bearing type.
- The following two digits identify the ISO dimension series. The first digit indicates the width (B, T) in the case of radial bearings or height (H) in the case of thrust bearings. The second digit identifies the outer diameter series (D).
- The last two digits of the basic designation identify the size code of the bearing bore. The size code multiplied by 5 gives the bore diameter (d) in mm.

However, there are some important exceptions to this system.

Soure: SKF Handbook

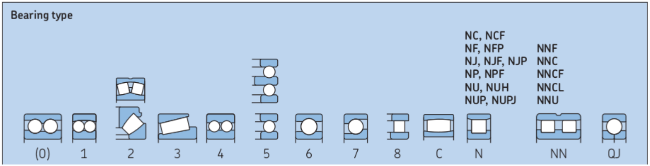
Bearing Designation: Naming System Exceptions

The most important exceptions in the designation system are:

- In a few cases the digit for the bearing type or the first digit of the dimension series identification is omitted. These digits are shown in brackets in the bearing series examples below.

Bearing series

(0)	1	2	3	4	5	6	7	8	C	N	NN	QJ
						6(0)4						
					544	623				(0)4		
		223			524	6(0)3				33		
		213			543	622				23		
		232			523	6(0)2				(0)3		
		222			542	630			23	22		
		241			522	6(1)0			32	12		
		231				16(0)0			22	(0)2		
		240	323		534	639			41	31	41	
		230	313		514	619			31	30	31	
		249	303		533	609			60	20	60	
	139	239	332		513	638	7(0)4	814	50	10	50	
	130	248	322		532	628	7(0)3	894	40	39	40	23
	(1)23	238	302		512	618	7(0)2	874	30	29	30	(0)3
	1(0)3		331		511	608	7(1)0	813	69	19	69	12
	(1)22	294	330		510	637	719	893	59	38	49	(0)2
(0)33	1(0)2	293	320	4(2)3	591	627	718	812	49	28	39	10
(0)32	1(1)0	292	329	4(2)2	590	617	708	811	39	18	48	19



Source: SKF Handbook

Bearing Designation

Naming System Exceptions

- Bearings with a bore diameter of 10, 12, 15 or 17 mm have the following size code identifications:
  00 : 10 mm
  01 : 12 mm
  02 : 15 mm
  03 : 17 mm
- For bearings with a bore diameter d < 10 mm or ≥ 500 mm, the bore diameter is left uncoded and is generally given directly in mm. An oblique stroke separates this uncoded number from the rest of the designation. E.g. 618/8 (d $= 8$ mm) or 511/530 (d $= 530$ mm).

Source: SKF Handbook

Bearing Designation

Naming System Exceptions

- For some bearings with a bore diameter less than 10 mm, such as deep groove, self-aligning and angular contact ball bearings, the bore diameter is also given in mm (uncoded) but is not separated from the rest of the designation by an oblique stroke, e.g. 629 or 129 ($d = 9$ mm).[5]
- Bore diameters that deviate from the standard bore diameters of a bearing are uncoded and given in mm up to three decimal places. This bore diameter identification is part of the basic designation and is separated by an oblique stroke. E.g. 6202/15.875 ($d = 15.875$ mm).

Source: SKF Handbook

[5] Please don't ask me why they came up with this system!

References

- SKF Rolling Bearings Catalogue [Link]
- NTN Rolling Bearings Handbook [Link]
- Timken Engineering Manual [Link]