Rolling-Contact Bearings

Also called "antifriction bearings" or "rolling bearings". The starting friction is about twice the running friction. Different from journal bearings in that the load is transferred by elements in rolling contact rather than sliding. With rolling bearings we do not design the bearing but rather we select a bearing according to our design requirements (*the bearings are already designed*).

Bearing Types

Bearings are designed to take radial load or thrust load or combination of both.

- Nomenclature of ball bearings;

❖ Four main parts: inner ring, outer ring, balls (or rollers) & separator (retainer).

❖ How balls are inserted in the grooves?

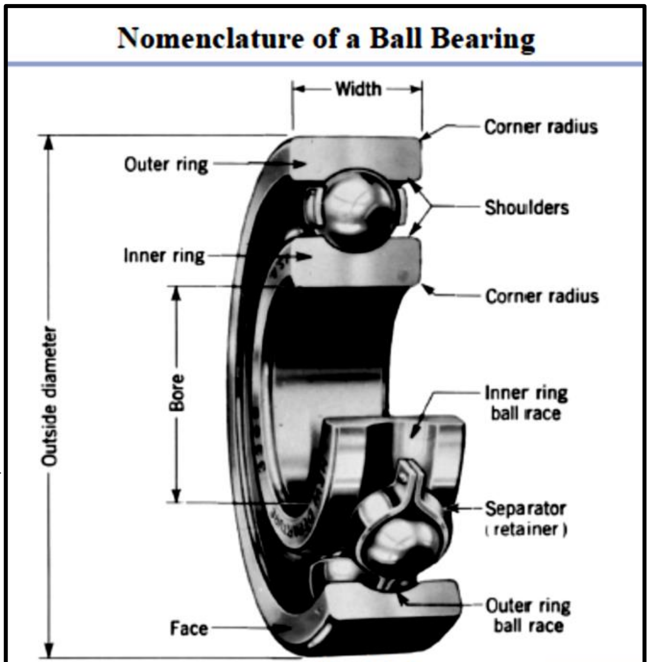


Fig. 11–1

- Some types of ball bearings: see *fig. **11-2***.

(a) ***Deep groove bearing***: takes radial and some thrust load.
(b) ***Filling notch bearing***: has more balls i.e. takes more radial load, but less thrust.
(c) ***Angular contact bearing***: more thrust.
(d, e) ***Shielded & sealed bearings***: protection against dirt.
(f, h) ***Self-aligning bearings***: withstands more misalignment.
(g) ***Double row bearing***: takes twice the load of single row, but less parts and space than two bearings.
(i, j) ***Thrust bearings***: thrust load only.

- Some types of roller bearings: see ***fig. 11-3.***

(a) ***Straight roller bearing***: takes higher radial load than ball bearing (more contact area), but needs perfect geometry & does not take thrust load.
(b) ***Spherical-roller thrust bearing***: useful for heavy loads & misalignment (contact area increases with load).

(c) ***Thrust***: thrust load only.

(d) ***Needle bearing***: useful when radial space is limited.

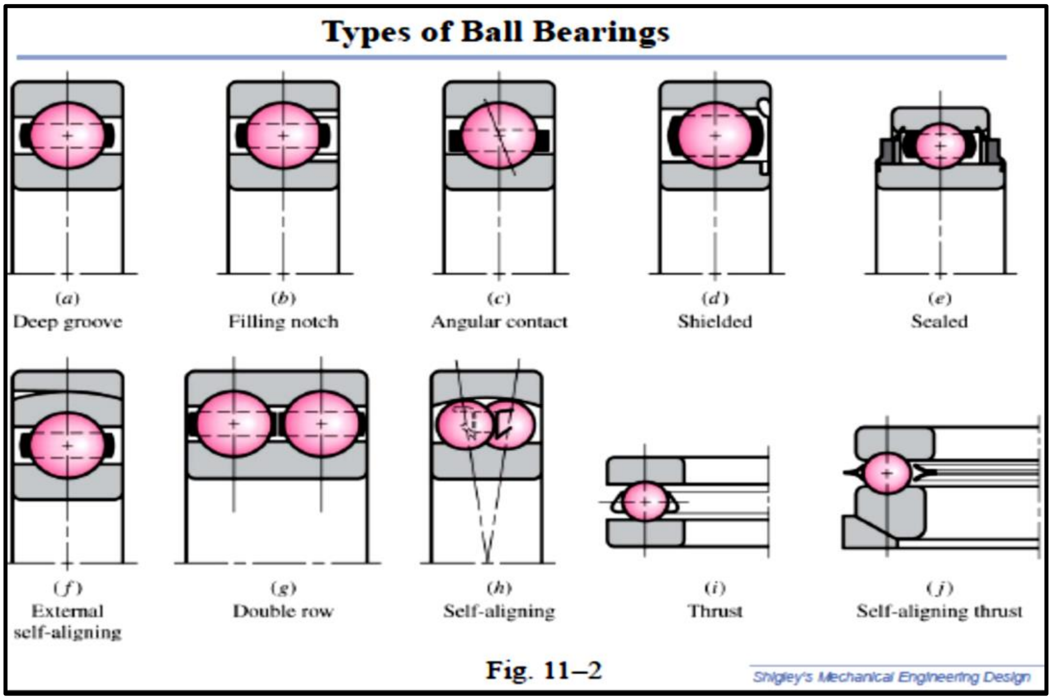


Fig. 11–2

(e, f) ***Tapered-roller bearings***: take both radial & thrust loads (higher loads than ball bearings).

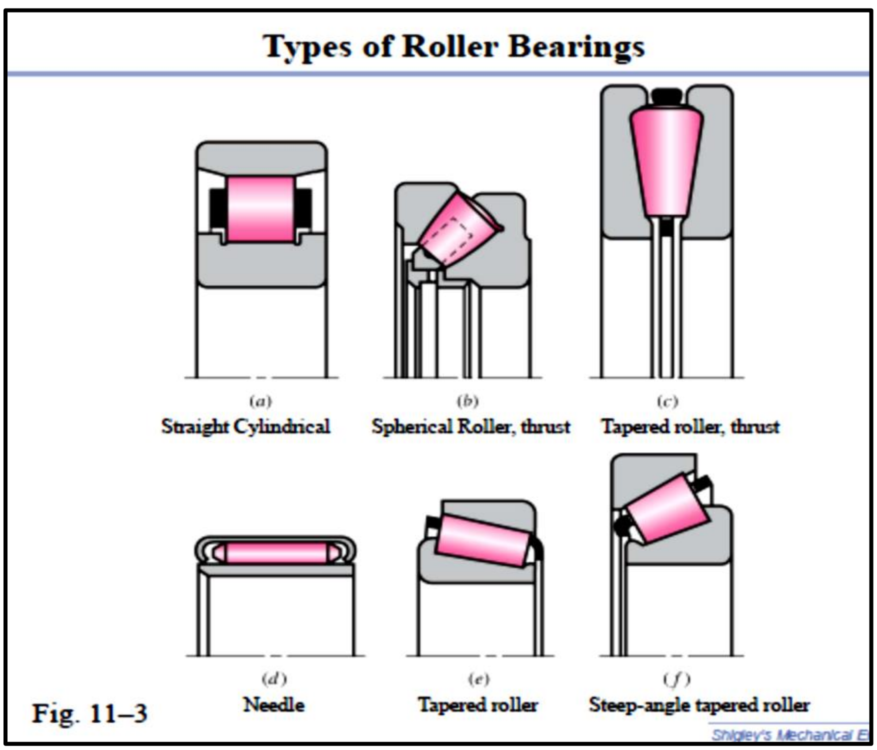


Fig. 11–3

❖ Other types:

- **Instrument bearings**: high precision, made of stainless steel.
- **Non precision**: no separator, made of sheet metal.
- **Ball bushings**: permit rotation & sliding.

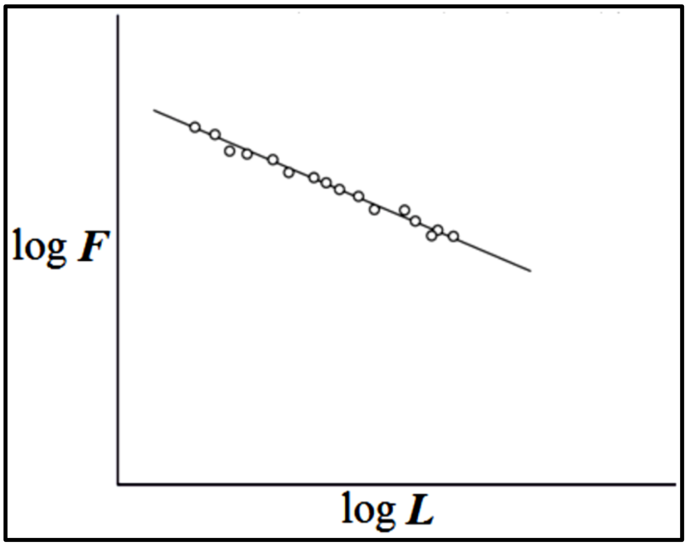
Bearing Life

When a bearing is in operation, contact stresses occur on the inner ring, rolling elements and outer ring.
If the bearing is clean, lubricated, sealed against dust and operates at reasonable temperature, then metal fatigue will be the only cause of failure.

- Bearing life is a measure of the "Number of revolutions of the inner ring (*outer ring is fixed*)" or "Number of hours of use (at a standard speed)" until the first evidence of fatigue.
  - According to *ABMA*, "*Rating life*" or minimum life or "$\mathbf{L_{10}}$ " life or "$\mathbf{B_{10}}$ " life is the number of revolutions (*or hours at fixed speed*) that *90%* of a group of bearings will achieve or exceed before failure criterion develops.
  - Median or average life refers to ***5o***thpercentile life of a group of bearings. It can be up to 4 or 5 times the $\mathbf{L_{10}}$ life.
  - Catalog Load Rating, C10: Constant radial load that causes 10% of a group of bearings to fail at the bearing manufacturer's rating life.
    ◦Depends on type, geometry, accuracy of fabrication, and material of bearing
    ◦Also called Basic Dynamic Load Rating, and Basic Dynamic Capacity
  - Basic Load Rating, C: A catalog load rating based on a rating life of 106 revolutions of the inner ring.
    ◦The radial load that would be necessary to cause failure at such a low life is unrealistically high.
    ◦The Basic Load Rating is a reference value, not an actual load.

Bearing Load-Life Relation at Rated Reliability

When identical groups of bearings are tested till life-failure criterion at different loads, the data can be plotted as the load vs. life on log-log scale is approximately linear.



- Thus, we can write: $FL^{1\backslash a} = Const.$ **(11–1)**

where,

$$\begin{cases} a = 3 & \textit{for Ball bearings} \\ a = 10/3 & \textit{for Roller bearings} \end{cases}$$

Obtained from testing

Applying Eq. (11–1) to two load-life conditions :

$$F_1 L_1^{1/a} = F_2 L_2^{1/a} \qquad (11\text{–}2)$$

- Manufacturers rate their bearings for a fixed number of revolutions at a certain radial load called the "*catalog load rating*" C_{10} .

- For example:

SKF rates for ***10⁶*** revolutions
Timken rates for ***90×10⁶*** revolutions

To choose a bearing from the catalog we can replace $\mathbf{F_1}$ and $\mathbf{F_2}$ with catalog values $\mathbf{C_{10}}$ and $\mathbf{L_{10}}$:

$$C_{10} L_{10}^{1/a} = F L^{1/a}$$

L in revolutions

or

$$C_{10}(\ell_R n_R 60)^{1/a} = F_D(\ell_D n_D 60)^{1/a}$$

- C_{10}: Catalog load rating *(KN or lb)*
- ℓ_R: Rating life *(hours)*
- n_R: Rating speed *(rev/min)*
- F_D: Desired load *(KN or lb)*
- ℓ_D: Desired life *(hours)*
- n_D: Desired speed *(rev/min)*

Solving for C_{10} gives:

$$C_{10} = F_D \left(\frac{\ell_D n_D 60}{\ell_R n_R 60} \right)^{1/a} \qquad (11\text{–}3)$$

EXAMPLE 11–1 Consider SKF, which rates its bearings for 1 million revolutions, so that L_{10} life is $60 L_R n_R = 10^6$ revolutions. The $L_R n_R 60$ product produces a familiar number. Timken, for example, uses $90(10^6)$ revolutions. If you desire a life of 5000 h at 1725 rev/min with a load of 400 lbf with a reliability of 90 percent, for which catalog rating would you search in an SKF catalog?

Solution From Eq. (11–3),

$$C_{10} = F_D \left(\frac{L_D n_D 60}{L_R n_R 60} \right)^{1/a} = 400 \left[\frac{5000(1725)60}{10^6} \right]^{1/3} = 3211 \text{ lbf} = 14.3 \text{ kN}$$

If a bearing manufacturer rates bearings at 500 h at $33\frac{1}{3}$ rev/min with a reliability of 0.90, then $L_R n_R 60 = 500(33\frac{1}{3})60 = 10^6$ revolutions. The tendency is to substitute 10^6 for $L_R n_R 60$ in Eq. (11–3). Although it is true that the 60 terms in Eq. (11–3) as displayed cancel algebraically, they are worth keeping, because at some point in your keystroke sequence on your hand-held calculator the manufacturer's magic number (10^6 or some other number) will appear to remind you of what the rating basis is and those manufacturers' catalogs to which you are limited. Of course, if you evaluate the bracketed quantity in Eq. (11–3) by alternating between numerator and denominator entries, the magic number will not appear and you will have lost an opportunity to check.

Relating Load, Life and Reliability

The catalog gives load rating for *0.9* reliability "$\mathbf{C_{10}}$"

Q: what if we desire a higher reliability?

A: Since bearing life is a random variable that follows a *Weibull* distribution, the catalog load rating "$\mathbf{C_{10}}$" can be found as:

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

For $R \geq 0.9$

where,

a_f : Application factor to compensate for non-steady load.

R_D : Desired reliability.

$x_0, \theta \,\&\, b$: Weibull parameters.

x_D : Non-dimensional life measure where:

$$X_D = \frac{L}{L_{10}} = \frac{60\ell_D n_D}{60\ell_R n_R}$$

Note that if $R_D = 0.9$ is used this will give the same result as the previous equation.

Also, a_f can be included in the previous equation.

The typical values of the Weibull distribution parameters for ball bearings are $\boldsymbol{x_o = 0.02, \theta = 4.459 \,\&\, b = 1.483}$ where $\boldsymbol{x_o}$ and $\boldsymbol{\theta}$ are in million revolutions.

Q: why would we need a reliability higher than 0.9?

A: take for example a gearbox having six bearings each with 0.9 reliability.

The total reliability will be: $(0.9)^6 = 0.53$ Only!

EXAMPLE 11–3 The design load on a ball bearing is 413 lbf and an application factor of 1.2 is appropriate. The speed of the shaft is to be 300 rev/min, the life to be 30 kh with a reliability of 0.99. What is the C_{10} catalog entry to be sought (or exceeded) when searching for a deep-groove bearing in a manufacturer's catalog on the basis of 10^6 revolutions for rating life? The Weibull parameters are $x_0 = 0.02$, $(\theta - x_0) = 4.439$, and $b = 1.483$.

Solution

$$x_D = \frac{L}{L_{10}} = \frac{60 L_D n_D}{60 L_R n_R} = \frac{60(30\,000)300}{10^6} = 540$$

Thus, the design life is 540 times the L_{10} life. For a ball bearing, $a = 3$. Then, from Eq. (11–7),

Answer

$$C_{10} = (1.2)(413)\left[\frac{540}{0.02 + 4.439(1 - 0.99)^{1/1.483}}\right]^{1/3} = 6696 \text{ lbf}$$

Combined Radial and Thrust Loading

Ball bearings are capable of resisting both radial and thrust loading.

- Let F_a & F_r be the axial (*thrust*) and radial loads and take "F_e" as the "*equivalent radial load*" (i.e., it will do the same damage as both).
  - Also, define a "*rotation factor*", V, such that:

$$\begin{cases} V = 1 & \text{when inner ring rotates} \\ V = 1.2 & \text{when outer ring rotates} \quad \text{why?} \end{cases}$$

Note that if the bearing is subjected to radial load only, the rotation factor V can be included directly in the equation used for calculating C_{10} by multiplying the design load F_D with V.

  - From testing it was found that F_e can be represented as:

$$F_e = X_i V F_r + Y_i F_a \qquad (11\text{–}9)$$

where,

$$\begin{cases} i = 1 & \text{when } F_a / VF_r \le e \\ i = 2 & \text{when } F_a / VF_r > e \end{cases}$$

❖ *Table 11-1* gives the values of X_1, X_2, Y_1, Y_2

  - "e" depends on F_a / C_o (calculate F_a / C_o then take the corresponding e value).

Note that C_o needs to be known (i.e., a bearing must be selected) to find F_e. Thus, an iterative solution is needed when the bearing is loaded by radial and thrust loads as will be seen later in Example 11-7.

Table 11–1

Equivalent Radial Load Factors for Ball Bearings

		$F_a/(VF_r) \le e$		$F_a/(VF_r) > e$	
F_a/C_0	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 $F_a/C_0 < 0.014$.

- The *ABMA* identifies the boundary dimensions of bearings using a two-digit number called the "*dimension-series code*" where the first digit refers to the width and the second refers to the height.

- See *fig. 11-7* (variety of bearings sizes that may have the same bore)

Figure 11-7

The basic ABMA plan for boundary dimensions. These apply to ball bearings, straight roller bearings, and spherical roller bearings, but not to inch-series ball bearings or tapered roller bearings. The contour of the corner is not specified. It may be rounded or chamfered, but it must be small enough to clear the fillet radius specified in the standards.

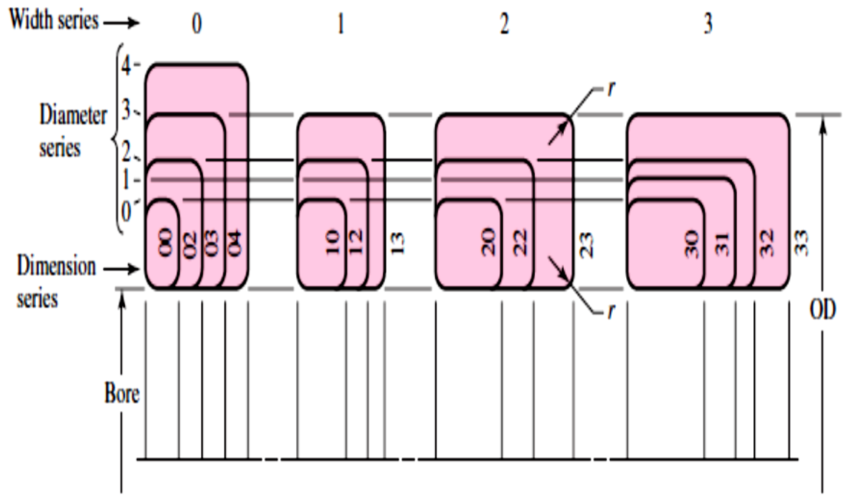


Table 11-2 lists the dimensions and load ratings C_{10} and C_0 for two types of the ***02-series*** ball bearings (*from the SKF catalogue*).

Table 11–2

Dimensions and Load Ratings for Single-Row 02-Series Deep-Groove and Angular-Contact Ball Bearings

Bore, mm	OD, mm	Width, mm	Fillet Radius, mm	Shoulder Diameter, mm d_S	Shoulder Diameter, mm d_H	Load Ratings, kN Deep Groove C_{10}	Deep Groove C_0	Angular Contact C_{10}	Angular Contact C_0
10	30	9	0.6	12.5	27	5.07	2.24	4.94	2.12
12	32	10	0.6	14.5	28	6.89	3.10	7.02	3.05
15	35	11	0.6	17.5	31	7.80	3.55	8.06	3.65
17	40	12	0.6	19.5	34	9.56	4.50	9.95	4.75
20	47	14	1.0	25	41	12.7	6.20	13.3	6.55
25	52	15	1.0	30	47	14.0	6.95	14.8	7.65
30	62	16	1.0	35	55	19.5	10.0	20.3	11.0
35	72	17	1.0	41	65	25.5	13.7	27.0	15.0
40	80	18	1.0	46	72	30.7	16.6	31.9	18.6
45	85	19	1.0	52	77	33.2	18.6	35.8	21.2
50	90	20	1.0	56	82	35.1	19.6	37.7	22.8
55	100	21	1.5	63	90	43.6	25.0	46.2	28.5
60	110	22	1.5	70	99	47.5	28.0	55.9	35.5
65	120	23	1.5	74	109	55.9	34.0	63.7	41.5
70	125	24	1.5	79	114	61.8	37.5	68.9	45.5
75	130	25	1.5	86	119	66.3	40.5	71.5	49.0
80	140	26	2.0	93	127	70.2	45.0	80.6	55.0
85	150	28	2.0	99	136	83.2	53.0	90.4	63.0
90	160	30	2.0	104	146	95.6	62.0	106	73.5
95	170	32	2.0	110	156	108	69.5	121	85.0

- The C_0 is called the "*static load rating*" which is the maximum radial load a

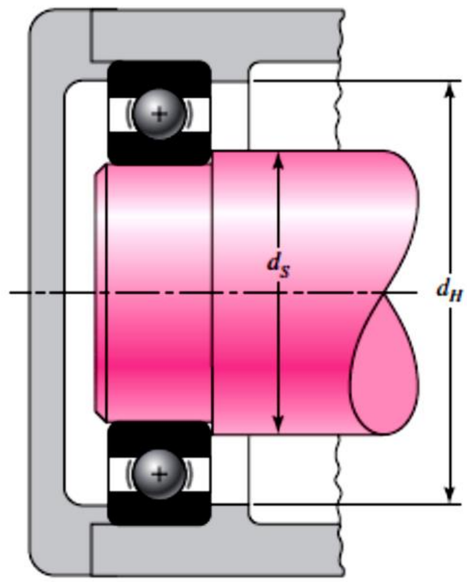
bearing can withstand while it is not rotating.

- C_0 value depends on the number and dimensions of the balls or rollers in the bearing).

* *Why is the C_0 value smaller than the C_{10} value?*
* What is the importance of the fillet radius and shoulder diameter? (See *fig. 11-8*)

Figure 11-8

Shaft and housing shoulder diameters d_S and d_H should be adequate to ensure good bearing support.



□ *Table 11-3* lists the dimensions and load ratings for some cylindrical-roller bearings (*from the SKF catalogue*)

Table 11-3

Dimensions and Basic Load Ratings for Cylindrical Roller Bearings

	02-Series				03-Series			
Bore, mm	OD, mm	Width, mm	Load Rating, kN C_{10}	Load Rating, kN C_0	OD, mm	Width, mm	Load Rating, kN C_{10}	Load Rating, kN C_0
25	52	15	16.8	8.8	62	17	28.6	15.0
30	62	16	22.4	12.0	72	19	36.9	20.0
35	72	17	31.9	17.6	80	21	44.6	27.1
40	80	18	41.8	24.0	90	23	56.1	32.5
45	85	19	44.0	25.5	100	25	72.1	45.4
50	90	20	45.7	27.5	110	27	88.0	52.0
55	100	21	56.1	34.0	120	29	102	67.2
60	110	22	64.4	43.1	130	31	123	76.5
65	120	23	76.5	51.2	140	33	138	85.0

70	125	24	79.2	51.2	150	35	151	102
75	130	25	93.1	63.2	160	37	183	125
80	140	26	106	69.4	170	39	190	125
85	150	28	119	78.3	180	41	212	149
90	160	30	142	100	190	43	242	160
95	170	32	165	112	200	45	264	189
100	180	34	183	125	215	47	303	220
110	200	38	229	167	240	50	391	304
120	215	40	260	183	260	55	457	340
130	230	40	270	193	280	58	539	408
140	250	42	319	240	300	62	682	454
150	270	45	446	260	320	65	781	502

▪To assist the designer in bearing selection, bearing manufacturers give some recommendations on bearing life (see *Table 11-4*) and load application factor (see *Table 11-5*).

Table 11–4

Bearing-Life Recommendations for Various Classes of Machinery

Type of Application	Life, kh
Instruments and apparatus for infrequent use	Up to 0.5
Aircraft engines	0.5–2
Machines for short or intermittent operation where service interruption is of minor importance	4–8
Machines for intermittent service where reliable operation is of great importance	8–14
Machines for 8-h service that are not always fully utilized	14–20
Machines for 8-h service that are fully utilized	20–30
Machines for continuous 24-h service	50–60
Machines for continuous 24-h service where reliability is of extreme importance	100–200

Table 11–5

Load-Application Factors

Type of Application	Load Factor
Precision gearing	1.0–1.1
Commercial gearing	1.1–1.3
Applications with poor bearing seals	1.2
Machinery with no impact	1.0–1.2
Machinery with light impact	1.2–1.5
Machinery with moderate impact	1.5–3.0

EXAMPLE 11–4 An SKF 6210 angular-contact ball bearing has an axial load F_a of 400 lbf and a radial load F_r of 500 lbf applied with the outer ring stationary. The basic static load rating C_0 is 4450 lbf and the basic load rating C_{10} is 7900 lbf. Estimate the L_{10} life at a speed of 720 rev/min.

Solution $V = 1$ and $F_a/C_0 = 400/4450 = 0.090$. Interpolate for e in Table 11–1:

F_a/C_0	e	
0.084	0.28	
0.090	e	from which $e = 0.285$
0.110	0.30	

$F_a/(VF_r) = 400/[(1)500] = 0.8 > 0.285$. Thus, interpolate for Y_2:

F_a/C_0	Y_2	
0.084	1.55	
0.090	Y_2	from which $Y_2 = 1.527$
0.110	1.45	

From Eq. (11–9),

$$F_e = X_2VF_r + Y_2F_a = 0.56(1)500 + 1.527(400) = 890.8 \text{ lbf}$$

With $L_D = L_{10}$ and $F_D = F_e$, solving Eq. (11–3) for L_{10} gives

Answer
$$L_{10} = \frac{60L_Rn_R}{60n_D}\left(\frac{C_{10}}{F_e}\right)^a = \frac{10^6}{60(720)}\left(\frac{7900}{890.8}\right)^3 = 16\,150 \text{ h}$$

Variable Loading

Bearing loads are frequently variable, it can be:

- Piecewise constant loading in cyclic pattern.
- Continuously variable loading in repeatable pattern.
- Random.

Let us consider the piecewise constant pattern, eqn. (1) can be written as:

$$F^aL = Constant = K \qquad (a)$$

- **If the bearing runs at load level F_1 until point *A*, then the partial damage can be measured as:**

$$D = F_1^a l_A$$

- **Consider the piecewise constant loading pattern shown.**

Figure 11–9 is a plot of *Fa* as ordinate and *L* as abscissa for Eq. (*a*). If a load level of *F*1 is selected and run to the failure criterion, then the area under the *F*1-*L*1 trace is numerically equal to *K*.

Figure 11–9

Plot of F^a as ordinate and L as abscissa for $F^a L$ = constant. The linear damage hypothesis says that in the case of load F_1, the area under the curve from $L = 0$ to $L = L_A$ is a measure of the damage $D = F_1^a L_A$. The complete damage to failure is measured by $C_{10}^a L_B$.

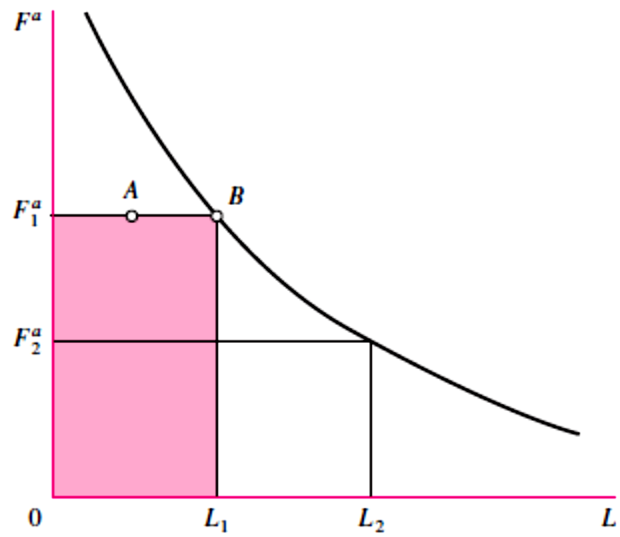
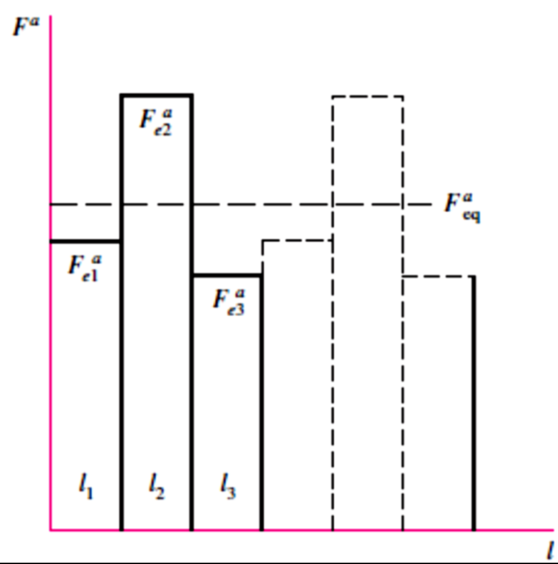


Figure 11–10

A three-part piecewise-continuous periodic loading cycle involving loads F_{e1}, F_{e2}, and F_{e3}. F_{eq} is the equivalent steady load inflicting the same damage when run for $l_1 + l_2 + l_3$ revolutions, doing the same damage D per period.



The damage done by loads F_{e1}, F_{e2} & F_{e3} is,

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

where,

F_{ei} : is equivalent radial load for combined radial-thrust loads.

L_i : is the number of revolutions.

- The equivalent steady load "F_{eq}" when run for $l_1 + l_2 + l_3$ revolutions, will do the same damage:

$$D = F_{eq}^a (l_1 + l_2 + l_3) \qquad \text{(c)}$$

- Equating and solving for F_{eq} we get,

$$F_{eq} = \left[\frac{F_{e1}^a l_1 + F_{e2}^a l_2 + F_{e3}^a l_3}{l_1 + l_2 + l_3} \right]^{1/a} = \left[\sum f_i F_{ei}^a \right]^{1/a} \qquad \text{(11–10)}$$

where f_i is the fraction of the total revolutions run under F_{ei}

Also, we can include the application factor ($\mathbf{a}_f$) for each segment Fei as $(\mathbf{a}_{fi}\, \mathbf{F}_{ei})^{\mathbf{a}}$; then Eq. (11–10) can be written;

$$\boxed{F_{eq} = \left[\sum f_i (a_{fi} F_{ei})^a \right]^{1/a}} \qquad \text{(11–12)}$$