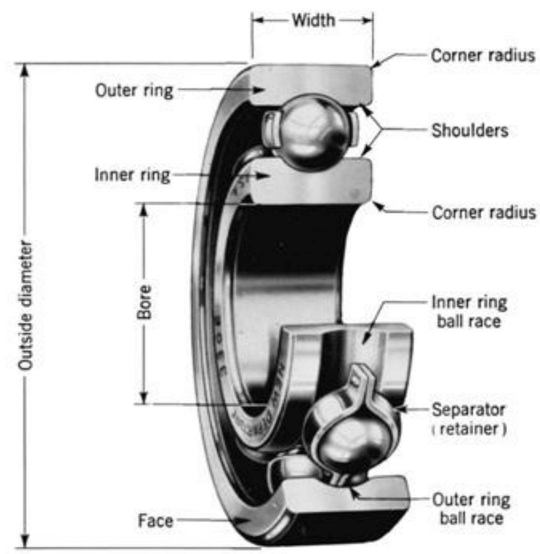
CH 11: Rolling-Contact Bearings

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 <u>rolling contact</u> rather than sliding.

With rolling bearings we do not design the bearing but rather we <u>select</u> a bearing according to our design requirements (*the bearings are already designed*).



Bearing Types

Bearings are designed to take <u>radial</u> load or <u>thrust</u> load or combination of <u>both</u>.

- Nomenclature of ball bearings;
  - Four main parts: inner ring, outer ring, balls (or rollers) & separator (retainer).
    - How balls are inserted in the grooves?

- Some types of <u>ball bearings</u>: see *fig. 11-2*.

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

- Some types of <u>roller bearings</u>: see *fig. 11-3*.

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

(c) *Thrust*: thrust load only.

- *Why rollers are tapered?*

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

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

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

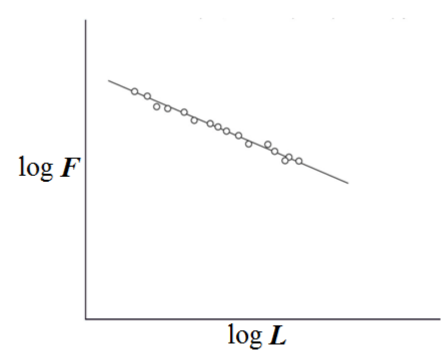
Bearing Life

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 "L_{10}" life or "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 *50th* percentile life of a group of bearings. It can be up to 4 or 5 times the L_{10} life.

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:



Obtained from testing

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

  where,

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

From *eqn. (1)* we can write:

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

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

  - For example:

    <u>*SKF*</u> rates for ***10***^{6} revolutions

    <u>*Timken*</u> rates for ***90×10***^{6} revolutions

- To choose a bearing from the catalog we can replace F_1 and L_1 with catalog values C_{10} and 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:

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

*See **Example 11-1** from text*

<u>Relating Load, Life and Reliability</u>

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

<u>***Q:***</u> what if we desire a <u>higher reliability</u>?

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

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

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 SKF ball bearings are $x_o = 0.02, \theta = 4.459 \,\&\, b = 1.483$ where x_o and θ 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!*

*See **Example 11-3** from text*

- The *ABMA* identifies the boundary dimensions of bearings using a 2-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)

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

- The C_o is called the "*static load rating*" which is the maximum radial load a bearing can withstand while it is not rotating.
  - C_o value depends on the number and dimensions of the balls or rollers in the bearing).

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

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

* Why the shoulder diameter is not listed?

❖ 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*).

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:

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

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:

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

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).

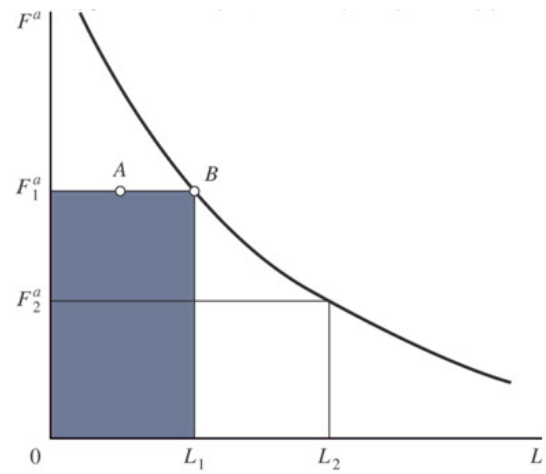
Note that C_o needs to be known (i.e., a bearing must be selected) to find F_e. Thus, an iterative solution is needed when the bearing is loaded by radial and thrust loads as will be seen later in Example 11-7.

*See **Example 11-4** from text*

Variable Loading

Bearing loads are frequently variable, it can be:

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



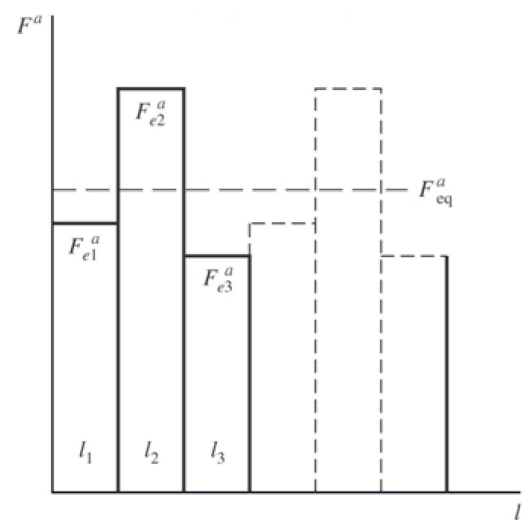
- Let us consider the piecewise constant pattern, eqn. (1) can be written as:

$$F^a L = Constant = K$$

- 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.



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:

$$D = F_{eq}^a (l_1 + l_2 + l_3)$$

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

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

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

- Also, we can include the application factor for each segment;

$$F_{eq} = \left[\sum f_i (a_{fi} F_{ei})^a\right]^{1/a}$$

*See **Example 11-5** from text*

Selection of Ball and Straight Roller Bearings

*See **Example 11-7** from text*

Selection of Tapered Roller Bearings

Tapered roller bearings are more complicated than ball and straight roller bearings.

- The four components of a tapered roller bearing are: cone (*inner ring*), cup (*outer ring*), tapered rollers and cage (*retainer*) see *fig. 11-13*.
- The assembled bearing consists of two separate parts:
  1. The cone assembly (*cone, rollers and cage*).
  2. The cup.
- Tapered roller bearing can carry radial or thrust loads or any combination of the two.
- Even if the bearing is under radial load only, because of the taper, a thrust reaction will be induced and it will try to separate the cone and cup assemblies.
  - One way to overcome this problem is to use two tapered roller bearings in opposite orientation "*direct or indirect mounting*" see *fig. 11-14*.
  - The induced axial component can be found as:

$$F_i = \frac{0.47 F_r}{K}$$

where, $K = 0.389 \cot\alpha$ and α is half the cup angle.

- Before a particular bearing is selected, an estimated value of $K = 1.5$ is used.

- *Fig. 11-15* shows a catalog page for tapered roller bearing from *Timken Company* [*90×10^6 rev. life*].

- To determine the equivalent design load for each bearing, first we need to identify the bearing that carries the external thrust load (*if any is present*) and label that bearing as *Bearing A* and the other one will be named *Bearing B* (see *fig. 11-17*).

  - Then, the equivalent design loads for each of the two bearings can be calculated as:

If $F_{iA} \leq (F_{iB} + F_{ae})$	➔	$F_{eA} = 0.4F_{rA} + K_A(F_{iB} + F_{ae})$ $F_{eB} = F_{rB}$
If $F_{iA} > (F_{iB} + F_{ae})$	➔	$F_{eB} = 0.4F_{rB} + K_B(F_{iA} - F_{ae})$ $F_{eA} = F_{rA}$

where,

F_{eA} & F_{eB}: are the equivalent radial loads for bearings A & B.
F_{rA} & F_{rB}: are the direct radial loads acting on bearings A & B.
F_{iA} & F_{iB}: are the induced axial loads on bearings A & B.
F_{ae}: is the external axial load.

*See **Example 11-8** from text*

Design Assessment for Selected Rolling-Contact Bearings

When we design a machine, each component (*e.g., gears, shafts, bearings, etc.*) is designed separately. However, the components interact and influence each other.

It is always a good check to do a design assessment after all elements have been designed (or selected) to make sure that all elements will perform as they are assumed to do.

- For example if the machine has several bearings we can do design assessment to check the reliability of each of them and the total reliability for all.

- For <u>ball and roller bearings</u>, solving for the reliability we get:

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

For $R \geq 0.9$

See ***Examples 11-9 & 11-10*** *from text*