Chapter 11

Bearings


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Chapter Outline

- Introduction
- Bearing Types
- Bearing Life
- Bearing Load Life at Rated Reliability
- Combined Radial and Thrust Loading
- Selection of Ball and Cylindrical Roller Bearings
- Selection of Tapered Roller Bearings
- Design Assessment for Selected Rolling-Contact Bearings
- Lubrication
- Mounting and Enclosure
A Bearing is a machine element that allows constrained relative motion between two parts, typically rotation or linear movement, and reduces friction between moving parts.

Bearings are used basically for performing three important tasks as mentioned below:

- Reducing friction
- Supporting the load
- Providing the guide for moving components such as shafts or wheels.

Bearings are classified broadly according to the type of operation, the motions allowed, or to the directions of the loads (forces) applied to the parts.
Bearing Types

- Bearings are manufactured to take pure radial loads, pure thrust loads, or a combination of the two kinds of loads.

- The nomenclature of a ball bearing is illustrated in Fig. 11–1, which also shows the four essential parts of a bearing.
  * Outer ring
  * Inner ring
  * Balls or rolling elements
  * Separator
Figure 11–1
Nomenclature of a ball bearing.
(General Motors Corp. Used with permission, GM Media Archives.)
There are many types of bearings, each used for different purposes. These include:

- Ball bearings,
- Ball thrust bearings,
- Roller bearings,
- Roller thrust bearings,
- Tapered roller thrust bearings.
Ball bearings

- Ball bearings, are probably the most common type of bearing. They are found in everything from inline skates to hard drives. These bearings can handle both radial and thrust loads, and are usually found in applications where the load is relatively small.

- In a ball bearing, the load is transmitted from the outer race to the ball, and from the ball to the inner race. Since the ball is a sphere, it only contacts the inner and outer race at a very small point, which helps it spin very smoothly. But it also means that there is not very much contact area holding that load, so if the bearing is overloaded, the balls can deform or squish, ruining the bearing.

Ball thrust bearings

- Ball thrust bearings are mostly used for low-speed applications and cannot handle much radial load. Wheelchair use this type of bearing.
Bearing Types

Some of the various types of standardized bearings that are manufactured are shown in Fig. 11–2.

Figure 11–2: Various types of ball bearings.
Bearing Types

Roller Bearings

- Roller bearings are used in applications like conveyor belt rollers, where they must hold heavy radial loads. In these bearings, the roller is a cylinder, so the contact between the inner and outer race is not a point but a line. This spreads the load out over a larger area, allowing the bearing to handle much greater loads than a ball bearing. However, this type of bearing is not designed to handle much thrust loading.

Roller thrust bearings

- Roller thrust bearings can support large thrust loads. They are often found in gear-sets like car transmissions between gears, and between the housing and the rotating shafts. The helical gears used in most transmissions have angled teeth -- this causes a thrust load that must be supported by a bearing.
Bearing Types

Tapered roller bearings

- Tapered roller bearings can support large radial and large thrust loads.
- Tapered roller bearings are used in car hubs, where they are usually mounted in pairs facing opposite directions so that they can handle thrust in both directions.
Bearing Types

Some of the large variety of standard roller bearings available are illustrated in Fig. 11–3.

**Figure 11-3**

Types of roller bearings:
- (a) straight roller;
- (b) spherical roller, thrust;
- (c) tapered roller, thrust;
- (d) needle;
- (e) tapered roller;
- (f) steep-angle tapered roller. *(Courtesy of The Timken Company.)*
Bearing Life

- **Bearing Failure**: Spalling or pitting of an area of 0.254 mm²

- **Life**: Number of revolutions (or hours at given speed) required for failure.
  - For one bearing

- **Rating Life**: Life required for 10% of sample to fail.
  - For a group of bearings
  - Also called Minimum Life or $L_{10}$ Life

- **Median Life**: Average life required for 50% of sample to fail.
  - For many groups of bearings
  - Also called Average Life or Average Median Life
  - Median Life is typically 4 or 5 times the $L_{10}$ Life
Bearing Load Life at Rated Reliability

Load Rating Definitions

- **Catalog Load Rating** \((C_{10})\): 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 \(10^6\) 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 at Rated Reliability

- **Static Load Rating** ($C_o$):
  Static radial load which corresponds to a permanent deformation of rolling element and race at the most heavily stressed contact of 0.0001$d$.
  - $d$ = diameter of roller
  - Used to check for permanent deformation
  - Used in combining radial and thrust loads into an equivalent radial load

- **Equivalent Radial Load** ($F_e$):
  Constant stationary load applied to bearing with rotating inner ring which gives the same life as actual load and rotation conditions.
Bearing Load Life at Rated Reliability

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,

\[ FL^{1/a} = \text{constant} \]  \hspace{1cm} (11-1)

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

Figure 11-4

Typical bearing load-life log-log curve.
Applying Eq. (11–1) to two load-life conditions,

\[ F_1 L_1^{1/a} = F_2 L_2^{1/a} \quad (11–2) \]

Denoting condition 1 with \( R \) for catalog rating conditions, and condition 2 with \( D \) for the desired design conditions,

\[ F_R L_R^{1/a} = F_D L_D^{1/a} \quad (a) \]

The units of \( L \) are revolutions. If life \( \mathcal{L} \) is given in hours at a given speed \( n \) in rev/min, applying a conversion of 60 min/h,

\[ L = 60 \mathcal{L} n \quad (b) \]

where \( \mathcal{L} \) is in hours, \( n \) is in rev/min, and 60 min/h is the appropriate conversion factor.
Bearing Load Life at Rated Reliability

Load-Life Relationship

Incorporating Eq. (b) into Eq. (a),

\[ F_R(L_Rn_R60)^{1/a} = F_D(L_Dn_D60)^{1/a} \]  \( (c) \)

catalog rating, lbf or kN
rating life in hours
rating speed, rev/min

desired speed, rev/min
desired life, hours
desired radial load, lbf or kN

Solving Eq. (c) for \( F_R \), which is just another notation for the catalog load rating,

\[ C_{10} = F_R = F_D \left( \frac{L_D}{L_R} \right)^{1/a} = F_D \left( \frac{L_Dn_D60}{L_Rn_R60} \right)^{1/a} \]  \( (11-3) \)

It is sometimes convenient to define \( x_D = \frac{L_D}{L_R} \) as a dimensionless multiple of rating life.
EXAMPLE 11–1

Consider SKF Ball bearings, which rates its bearings for 1 million revolutions. If you desire a life of 5000 h at 1725 rev/min with a load of 2 kN with a reliability of 90 percent, for which catalog rating would you search in an SKF catalog?

Solution

The rating life is \( L_{10} = L_R = \mathcal{L}_R n_R 60 = 10^6 \) revolutions. From Eq. (11–3),

Answer

\[
C_{10} = F_D \left( \frac{L_D n_D 60}{L_R n_R 60} \right)^{1/a} = 2 \left[ \frac{5000(1725)60}{10^6} \right]^{1/3} = 16.1 \text{ kN}
\]
A ball bearing is capable of resisting radial loading and a thrust loading. Furthermore, these can be combined.

Consider $F_a$ and $F_r$ to be the axial thrust and radial loads, respectively, and $F_e$ to be the equivalent radial load that does the same damage as the combined radial and thrust loads together.

A rotation factor $V$ is defined such that $V = 1$ when the inner ring rotates and $V = 1.2$ when the outer ring rotates. Two dimensionless groups can now be formed: $F_e / V F_r$ and $F_a / V F_r$. 

Combined Radial and Thrust Loading
When these two dimensionless groups are plotted as in Fig. 11–6, the data fall in a gentle curve that is well approximated by two straight-line segments.

The abscissa $e$ is defined by the intersection of the two lines. The equations for the two lines shown in Fig. 11–6 are

\[
\frac{F_e}{VF_r} = 1 \text{ when } \frac{F_a}{VF_r} \leq e \quad (11-8a)
\]

\[
\frac{F_e}{VF_r} = X + Y \frac{F_a}{VF_r} \text{ when } \frac{F_a}{VF_r} > e \quad (11-8b)
\]
Combined Radial and Thrust Loading

where, as shown, $X$ is the ordinate intercept and $Y$ is the slope of the line for $F_a / V F_r > e$. It is common to express Eqs. (11–8a) and (11–8b) as a single equation,

$$F_e = X_i V F_r + Y_i F_a$$  \hspace{2cm} (11–9)

where $i = 1$ when $F_a / V F_r \leq e$ and $i = 2$ when $F_a / V F_r > e$. The $X$ and $Y$ factors depend upon the geometry and construction of the specific bearing.

Table 11–1 lists representative values of $X_1$, $Y_1$, $X_2$, and $Y_2$ as a function of $e$, which in turn is a function of $F_a / C_0$, where $C_0$ is the basic static load rating.

The *basic static load rating* is the load that will produce a total permanent deformation in the raceway and rolling element at any contact point of 0.0001 times the diameter of the rolling element.
### Table 11-1

**Combined Radial and Thrust Loading**

<table>
<thead>
<tr>
<th>$F_a/C_0$</th>
<th>$e$</th>
<th>$F_a/(VF_r) \leq e$</th>
<th>$F_a/(VF_r) &gt; e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$X_1$</td>
<td>$Y_1$</td>
</tr>
<tr>
<td>0.014*</td>
<td>0.19</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>0.021</td>
<td>0.21</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>0.028</td>
<td>0.22</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>0.042</td>
<td>0.24</td>
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<tr>
<td>0.056</td>
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</tr>
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<td>0.070</td>
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</tr>
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<td>0.084</td>
<td>0.28</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>0.110</td>
<td>0.30</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>0.17</td>
<td>0.34</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>0.28</td>
<td>0.38</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>0.42</td>
<td>0.42</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>0.56</td>
<td>0.44</td>
<td>1.00</td>
<td>0</td>
</tr>
</tbody>
</table>

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

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Combined Radial and Thrust Loading

- The basic static load rating is typically tabulated, along with the basic dynamic load rating $C_{10}$, in bearing manufacturers’ publications. See Table 11–2, for example.

**Table 11-2**

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

<table>
<thead>
<tr>
<th>Bore, mm</th>
<th>OD, mm</th>
<th>Width, mm</th>
<th>Fillet Radius, mm</th>
<th>Shoulder Diameter, mm</th>
<th>Deep Groove Load Ratings, kN</th>
<th>Angular Contact Load Ratings, kN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$C_{10}$</td>
<td>$C_{0}$</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>9</td>
<td>0.6</td>
<td>12.5</td>
<td>5.07</td>
<td>2.24</td>
</tr>
<tr>
<td>12</td>
<td>32</td>
<td>10</td>
<td>0.6</td>
<td>14.5</td>
<td>6.89</td>
<td>3.10</td>
</tr>
<tr>
<td>15</td>
<td>35</td>
<td>11</td>
<td>0.6</td>
<td>17.5</td>
<td>7.80</td>
<td>3.55</td>
</tr>
<tr>
<td>17</td>
<td>40</td>
<td>12</td>
<td>0.6</td>
<td>19.5</td>
<td>9.56</td>
<td>4.50</td>
</tr>
<tr>
<td>20</td>
<td>47</td>
<td>14</td>
<td>1.0</td>
<td>25</td>
<td>12.7</td>
<td>6.20</td>
</tr>
<tr>
<td>25</td>
<td>52</td>
<td>15</td>
<td>1.0</td>
<td>30</td>
<td>14.0</td>
<td>6.95</td>
</tr>
<tr>
<td>30</td>
<td>62</td>
<td>16</td>
<td>1.0</td>
<td>35</td>
<td>19.5</td>
<td>10.0</td>
</tr>
<tr>
<td>35</td>
<td>72</td>
<td>17</td>
<td>1.0</td>
<td>41</td>
<td>25.5</td>
<td>13.7</td>
</tr>
<tr>
<td>40</td>
<td>80</td>
<td>18</td>
<td>1.0</td>
<td>46</td>
<td>30.7</td>
<td>16.6</td>
</tr>
<tr>
<td>45</td>
<td>85</td>
<td>19</td>
<td>1.0</td>
<td>52</td>
<td>33.2</td>
<td>18.6</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
<td>20</td>
<td>1.0</td>
<td>56</td>
<td>35.1</td>
<td>19.6</td>
</tr>
<tr>
<td>55</td>
<td>100</td>
<td>21</td>
<td>1.5</td>
<td>63</td>
<td>43.6</td>
<td>25.0</td>
</tr>
<tr>
<td>60</td>
<td>110</td>
<td>22</td>
<td>1.5</td>
<td>70</td>
<td>47.5</td>
<td>28.0</td>
</tr>
<tr>
<td>65</td>
<td>120</td>
<td>23</td>
<td>1.5</td>
<td>74</td>
<td>55.9</td>
<td>34.0</td>
</tr>
<tr>
<td>70</td>
<td>125</td>
<td>24</td>
<td>1.5</td>
<td>79</td>
<td>61.8</td>
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<td>75</td>
<td>130</td>
<td>25</td>
<td>1.5</td>
<td>86</td>
<td>66.3</td>
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<td>80</td>
<td>140</td>
<td>26</td>
<td>2.0</td>
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<td>85</td>
<td>150</td>
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<td>2.0</td>
<td>99</td>
<td>83.2</td>
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<td>90</td>
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<td>30</td>
<td>2.0</td>
<td>104</td>
<td>95.6</td>
<td>62.0</td>
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<tr>
<td>95</td>
<td>170</td>
<td>32</td>
<td>2.0</td>
<td>110</td>
<td>108</td>
<td>69.5</td>
</tr>
</tbody>
</table>
Combined Radial and Thrust Loading

- The bearings are identified by a two-digit number called the *dimension-series code*.
- The first number in the code is from the *width series*, 0, 1, 2, 3, 4, 5, and 6. The second number is from the *diameter series* (outside), 8, 9, 0, 1, 2, 3, and 4. Figure 11–7 shows the variety of bearings that may be obtained with a particular bore.

![Figure 11-7](image)

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.
Combined Radial and Thrust Loading

- The housing and shaft shoulder diameters listed in the tables should be used whenever possible to secure adequate support for the bearing and to resist the maximum thrust loads (Fig. 11–8). Table 11–3 lists the dimensions and load ratings of some straight roller bearings.
### Combined Radial and Thrust Loading

#### Table 11-3

Dimensions and Basic Load Ratings for Cylindrical Roller Bearings

<table>
<thead>
<tr>
<th>Bore, mm</th>
<th>OD, mm</th>
<th>Width, mm</th>
<th>Load Rating, kN</th>
<th>OD, mm</th>
<th>Width, mm</th>
<th>Load Rating, kN</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$C_{10}$</td>
<td>$C_0$</td>
<td></td>
<td>$C_{10}$</td>
</tr>
<tr>
<td>25</td>
<td>52</td>
<td>15</td>
<td>16.8</td>
<td>8.8</td>
<td>62</td>
<td>17</td>
</tr>
<tr>
<td>30</td>
<td>62</td>
<td>16</td>
<td>22.4</td>
<td>12.0</td>
<td>72</td>
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<td>22</td>
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<td>446</td>
<td>260</td>
<td>320</td>
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</table>
EXAMPLE 11–4

An SKF 6210 angular-contact ball bearing has an axial load $F_a$ of 1780 N and a radial load $F_r$ of 2225 N applied with the outer ring stationary. The basic static load rating $C_0$ is 19800 N and the basic load rating $C_{10}$ is 35150 N. Estimate the $L_{10}$ life at a speed of 720 rev/min.

Solution

$V = 1$ and $F_a / C_0 = 1780/19800 = 0.090$. Interpolate for $e$ in Table 11–1:

<table>
<thead>
<tr>
<th>$F_a / C_0$</th>
<th>$e$</th>
</tr>
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<tbody>
<tr>
<td>0.084</td>
<td>0.28</td>
</tr>
<tr>
<td>0.090</td>
<td>$e$</td>
</tr>
<tr>
<td>0.110</td>
<td>0.30</td>
</tr>
</tbody>
</table>

From which $e = 0.285$.
EXAMPLE 11–4

\[ \frac{F_a}{(V F_r)} = \frac{1780}{(1) 2225} = 0.8 > 0.285. \text{ Thus, interpolate for } Y_2: \]

<table>
<thead>
<tr>
<th>( \frac{F_a}{C_0} )</th>
<th>( Y_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.084</td>
<td>1.55</td>
</tr>
</tbody>
</table>
| 0.090          | \( Y_2 \) from which \( Y_2 = 1.527 \)
| 0.110          | 1.45   |

From Eq. (11–9),

\[ F_e = X_2 V F_r + Y_2 F_a = 0.56 (1) 2225 + 1.527 (1780) = 3964 \text{ N} \]

With \( \mathcal{L}_D = \mathcal{L}_{10} \) and \( F_D = F_e \), solving Eq. (11–3) for 10 gives

Answer

\[ \mathcal{L}_{10} = \frac{60 \mathcal{L}_R n_R}{60 n_D} \left( \frac{C_{10}}{F_e} \right)^a = \frac{10^6}{60(720)} \left( \frac{35150}{3964} \right)^3 = 16139.5 \text{ h} \]
The contacting surfaces in rolling bearings have a relative motion that is both rolling and sliding, and so it is difficult to understand exactly what happens. If the relative velocity of the sliding surfaces is high enough, then the lubricant action is hydrodynamic.

The purposes of an antifriction-bearing lubricant may be summarized as follows:

1. To provide a film of lubricant between the sliding and rolling surfaces
2. To help distribute and dissipate heat
3. To prevent corrosion of the bearing surfaces
4. To protect the parts from the entrance of foreign matter
**Lubrication**

- Either oil or grease may be employed as a lubricant. The following rules may help in deciding between them.

<table>
<thead>
<tr>
<th>Use Grease When</th>
<th>Use Oil When</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The temperature is not over 200°F.</td>
<td>1. Speeds are high.</td>
</tr>
<tr>
<td>2. The speed is low.</td>
<td>2. Temperatures are high.</td>
</tr>
<tr>
<td>3. Unusual protection is required from the entrance of foreign matter.</td>
<td>3. Oiltight seals are readily employed.</td>
</tr>
<tr>
<td>4. Simple bearing enclosures are desired.</td>
<td>4. Bearing type is not suitable for grease lubrication.</td>
</tr>
<tr>
<td>5. Operation for long periods without attention is desired.</td>
<td>5. The bearing is lubricated from a central supply which is also used for other machine parts.</td>
</tr>
</tbody>
</table>
Mounting and Enclosure

- The various bearing manufacturers’ handbooks give many mounting details in almost every design area.

- The most frequently encountered mounting problem is that which requires one bearing at each end of a shaft.

- Such a design might use one ball bearing at each end, one tapered roller bearing at each end, or a ball bearing at one end and a straight roller bearing at the other.
Mounting and Enclosure

Figure 11-20
A common bearing mounting.

Figure 11-21
An alternative bearing mounting to that in Fig. 11-20.
Mounting and Enclosure

Figure 11-22
Two-bearing mountings. (Courtesy of The Timken Company.)

Figure 11-23
Mounting for a washing-machine spindle. (Courtesy of The Timken Company.)
Mounting and Enclosure

Mounting angular-contact ball bearings

- When maximum stiffness and resistance to shaft misalignment is desired, pairs of angular-contact ball bearings (Fig. 11–24) are often used in an arrangement called **duplexing**.

- Three mounting arrangements are used:
  - The **face-to-face mounting**, called DF, will take heavy radial loads and thrust loads from either direction.
  - The **DB mounting (back to back)** has the greatest aligning stiffness and is also good for heavy radial loads and thrust loads from either direction.
  - The **tandem arrangement**, called the **DT mounting**, is used where the thrust is always in the same direction; since the two bearings have their thrust functions in the same direction.
Mounting and Enclosure

Arrangements of angular ball bearings

(a) DF mounting;

(b) DB mounting;

(c) DT mounting.
Mounting and Enclosure

Enclosure

- To exclude dirt and foreign matter and to retain the lubricant, the bearing mountings must include a seal.

- The three principal methods of sealings are the felt seal, the commercial seal, and the labyrinth seal (Fig. 11–26).

**Figure 11–26**

Typical sealing methods.
(General Motors Corp. Used with permission, GM Media Archives.)

(a) Felt seal  
(b) Commercial seal  
(c) Labyrinth seal
Mounting and Enclosure

Enclosure

- *Felt seals* may be used with grease lubrication when the speeds are low.

- The *commercial seal* is an assembly consisting of the rubbing element and, generally, a spring backing, which are retained in a sheet-metal jacket. These seals are usually made by press fitting them into a counterbored hole in the bearing cover.

- The *labyrinth seal* is especially effective for high-speed installations and may be used with either oil or grease. It is sometimes used with flingers.