Bearing Design

ME 313: Mechanical Design
Week 10

Today's Topics

- Overview of Bearings
- Rolling-contact bearings
  - Principles of rolling contact bearings
  - Type of rolling-contact bearings
  - Bearing life
  - Bearing reliability
- Journal bearings
  - Principles of journal bearings
  - Theory of lubrication

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Bearing Uses

- Device that allows constrained motions between two or more components

Bearing Categories

- Can be divided based on principles of operation or by allowed motions

Bearing Types by Allowed Motions

- Axial rotation
  - Shaft rotation
- Linear motion
  - drawer
- Spherical rotation
  - Ball and socket joint (shoulder)
- Hinged motion
  - Door, elbow, knee, etc.

Bearing Types by Principles of Operation

- Plain bearing
- Rolling-contact bearing
- Fluid bearing
- Jewel bearing
- Magnetic bearing
- Flexure bearing

Main Focus

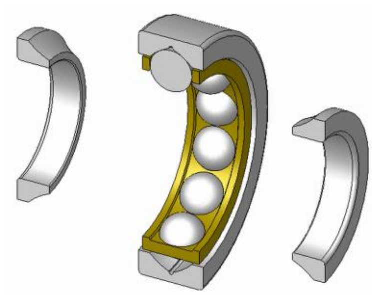
- Rolling-contact bearings
- Journal bearings

Rolling Element Bearings

- Bearing have rolling elements, which allows relative motions between two surfaces without sliding
- Rolling elements can be:
  - Balls
  - Needles
  - Cylinders (rollers)
  - Tapered rollers

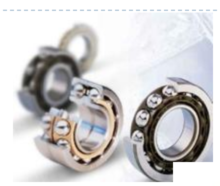
Ball Bearings

- Use to reduce rotational friction and support radial and axial loads



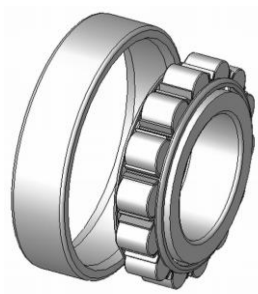
Typical Construction of Ball Bearing

- Angular Contact
  - For radial and axial load
- Axial
  - Mainly for axial load
- Deep groove
  - Groove size is close to ball diameter, enhancing load resistance but limiting misalignment



Roller/Needle Bearings

- Rollers are cylinders with slightly longer length than diameter
- Needles are cylindrical rollers but with small diameter and long



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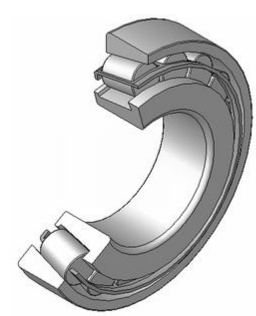
Tapered Roller Bearings

- Use to support large axial and radial load simultaneously
- Rollers are tapered
  - Each is a part of a cone



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Rolling Element Bearing Failure

- There are 3 major failure modes
  - Abrasion: heavy scratching on race surface
  - Fatigue: race or ball fracture due to repeated contact stress
  - Pressure-induced welding: metal bonding due to high pressure

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Bearing Life

- Bearing life is usually defined by
  - Number of revolutions of inner ring until first sign of failure
  - Number of hours of use at standard angular speed
- *Rating life* is a term used by most manufacturers
  - number of revolutions or hours than 90% of bearings will achieve before failure develops, L_{10}

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Bearing Load-Life Tradeoff at Constant Reliability

- Data from regression shows that

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

  - *F* is exerted load on bearing
  - *L* is bearing life
    - *a* = 3 for ball bearing
    - *a* = 10/3 for roller bearings (cylindrical and tapered rollers)

- Manufacturer choose to rate the load based on a set number of revolutions
  - The rated load is usually called *catalog load rating,* C_{10}

Catalog Load Rating and Rating Life

- We can relate load requirement to expected bearing life by

$$C_{10}L_{10}^{1/a} = FL^{1/a}$$

- Also can be converted to number of revolutions

$$C_{10}(60L_R n_R)^{1/a} = F_D(60L_D n_D)^{1/a}$$

  - *L* is life, in hours
  - *n* is angular speed, rev/min
  - Subscript:
    - *R* for rated
    - *D* for *desired*

Example

Bearing Survival: Reliability-Life Tradeoff

- At constant load, the longer bearing works, the lower its chance to continue working
  - follows a Weibull distribution

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

  - R = reliability
  - x = life
  - $x0$ = guaranteed or minimum value of life
  - theta = characteristic parameter
  - b = shape parameter

Load-Life-Reliability

- Combine the two previous equations, we have

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

Combined Radial and Thrust Loading

- When there are both radial and thrust loads, equivalent load needs to be calculated to determine bearing life

$$\frac{F_e}{VF_r} = 1 \quad \text{when} \quad \frac{F_a}{VF_r} \le e$$

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

  - depends on relative axial to radial load and whether inner or outer ring is rotating

General Form of Equivalent Load

- General form can be written as

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

  - V = 1 for inner ring rotates, = 1.2 for outer
  - i = 1 when $F_a / VF_r < e$ and i = 2 when $F_a / VF_r > e$

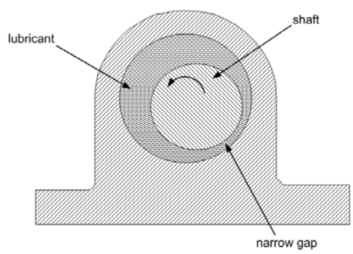
  - dependent on axial load compared to basic static load rating C_0

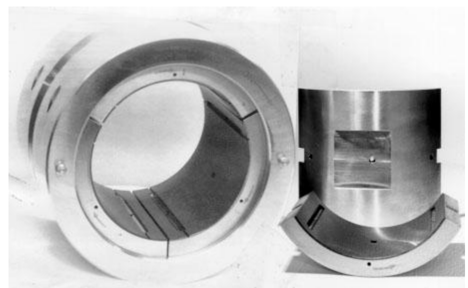
F_a/C_0	e	$F_a/VF_r < e$		$F_a/VF_r > e$	
		X_1	Y_1	X_2	Y_2
0.014	0.19	1	0	0.56	2.30
0.028	0.22	1	0	0.56	1.99
0.07	0.27	1	0	0.56	1.63
0.17	0.34	1	0	0.56	1.31
0.56	0.44	1	0	0.56	1.00

Example

Journal Bearing

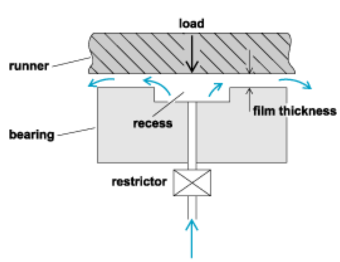
- Make uses of lubrication to reduce friction
  - no direct contact between two surfaces

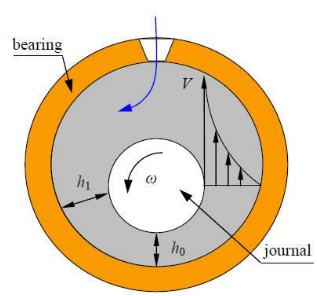




Types of Journal Bearings

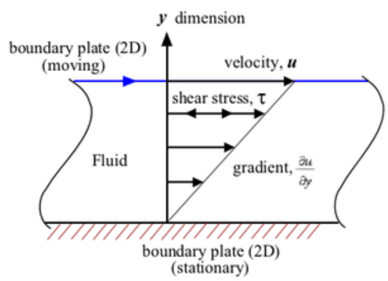
- Hydrostatically lubricated
  - external pump is needed to keep lubricant correctly pressurized
- Hydrodynamically lubricated
  - lubricant is pressurized by the motion of surfaces





Theory of Lubrication

- Required to understand the basics of how journal bearing works
  - Directly related to fluid mechanics



$$\tau = \frac{F}{A} = \mu \frac{du}{dy}$$

$$= \mu \frac{u}{h}$$

Petroff's Equation

- Assuming concentric shaft and housing

$$\tau = \mu \frac{u}{h} = \frac{2\pi r \mu N}{c}$$

- □ N is rotational speed (rev/s)
- □ r is shaft radius
- □ c is shaft-housing clearance

- Torque on the shaft is

$$T = (\tau A)(r) = \left(\frac{2\pi r \mu n}{c} \times 2\pi r l \right)(r) = \frac{4\pi^2 r^3 l \mu N}{c}$$

Frictional Torque

- Consider for W on bearing
  - pressure on shaft projected area is

$$P = \frac{W}{2rl}$$

  - frictional force is

$$friction = fW$$

  - torque due to friction is

$$frictional\,torque = fWr = f(2rlP)(r)$$
$$= 2r^2 flP$$

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Equivalent Coefficient of Friction

$$f = 2\pi^2 \frac{\mu N}{P} \frac{r}{c}$$

- This is called Petroff's equation
  - provides quick estimates for coefficient of friction of lightly loaded bearing
- Two important quantities to lubrication are

$$\frac{\mu N}{P} \quad and \quad \frac{r}{c}$$

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Heat Generated in Journal Bearing

- Constant shearing increases temperature of lubricant
  - flow rate of lubricant through a clearance is

$$\dot{m} = \frac{lc\rho u}{2} = lc\rho\pi rN$$

  - Heat loss by convection and radiation is

$$\dot{Q}_{loss} = U_0 A_0 (T_b - T_0) = \frac{U_0 A_0 (T_f - T_0)}{2}$$

  - Heat generated is from frictional torque

$$\dot{Q}_{gen} = 2\pi TN = 2\pi fWrN = 8\pi^3 \frac{\mu r^3 N^2 l}{c}$$

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Lubricant Temperature

- At steady state, heat generated is equal to heat loss

$$\dot{Q}_{loss} = \dot{Q}_{gen}$$

$$T_f = T_0 + \frac{16\pi^3 \mu N^2 l r^3}{U_0 A_0 c}$$

- Lubricant temperature usually should not go above approximately 120 C
  - unless lubricant manufacturer states a higher number

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Example