ME303 Introduction to Mechanical Design

Lecture 13
Bearings, Lubrication, Brakes & Couplings

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Agenda

Week 12, Wednesday, Nov 27, 2019

- Bearing
  - Types
  - Life
  - Reliability
  - Load
  - Relating Concepts
  - Selection
    Design Assessment
  - Lubrication
  - Mounting & Enclosure
- Clutches & Brakes
  - Static Analysis
  - Types
  - Energy Considerations
  - Friction Materials
- Couplings

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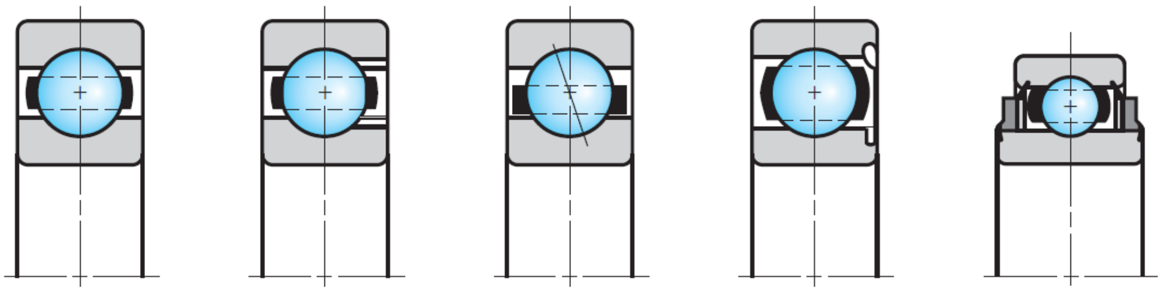
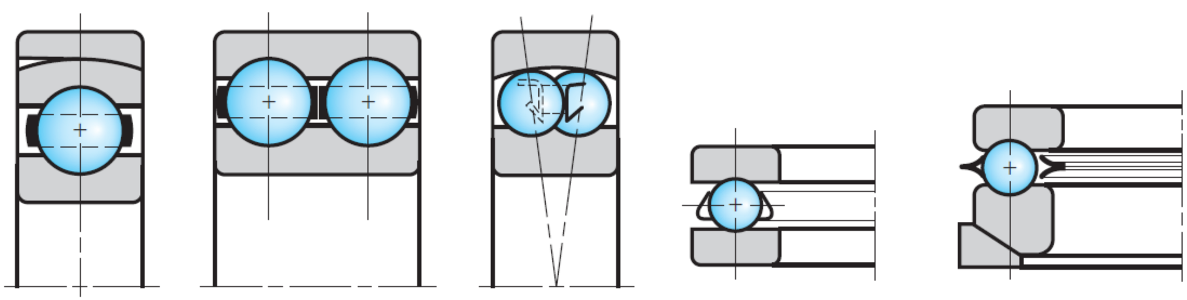
Rolling-Contact Bearing Types

The main load is transferred through elements in rolling contact.

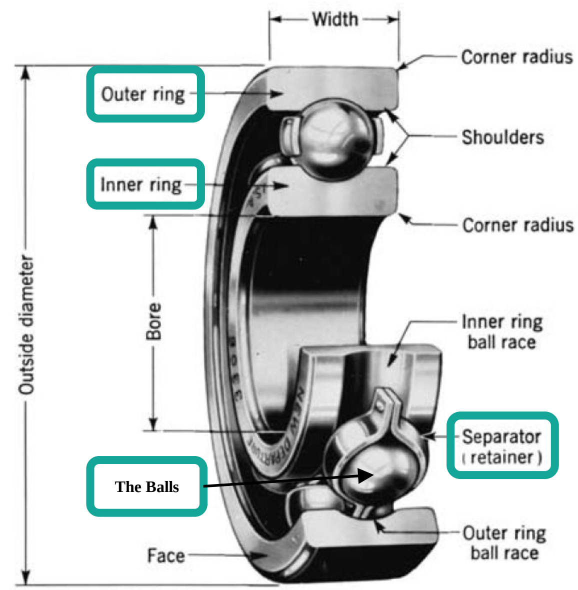
- Most bearing manufacturers provide engineering manuals and brochures containing lavish descriptions of the various types available.



(a) Deep groove
(b) Filling notch
(c) Angular contact
(d) Shielded
(e) Sealed



(f) External self-aligning
(g) Double row
(h) Self-aligning
(i) Thrust
(j) Self-aligning thrust



All these bearings may be obtained with shields on one or both sides.

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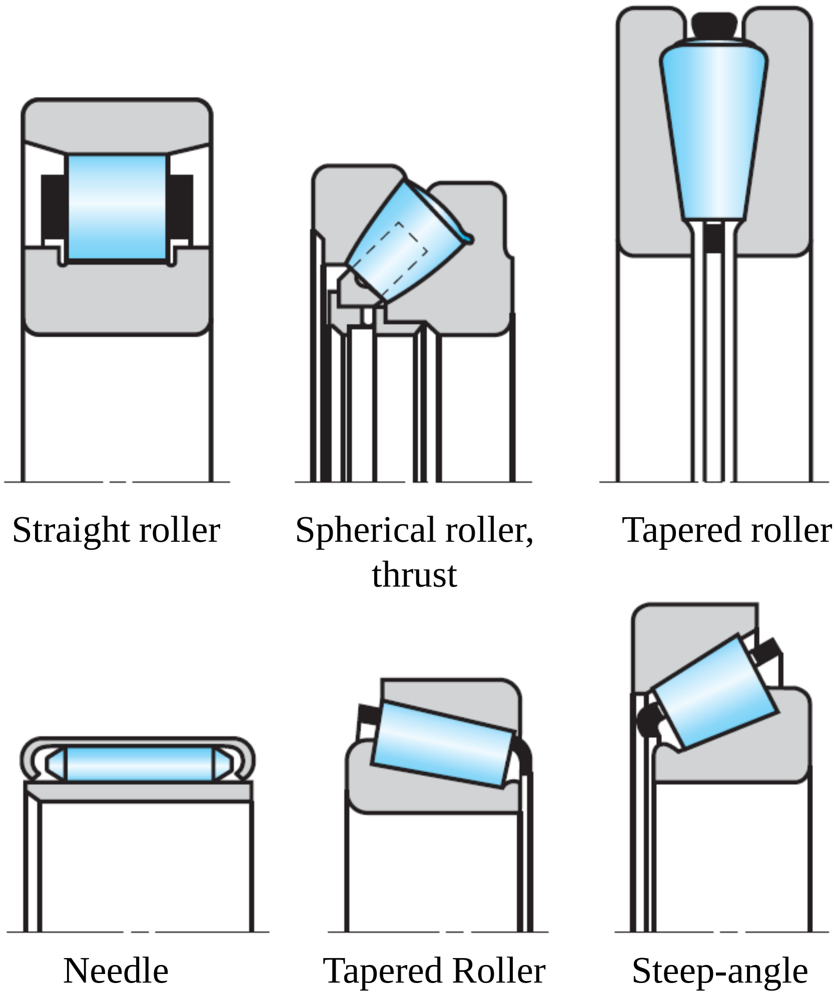
Types of Roller Bearings

What about the cost?

- Straight roller bearings
  - Carry a greater radial load than ball bearings of the same size because of the greater contact area.
  - Require almost perfect geometry of the raceways and rollers.
  - Straight roller bearings will not, of course, take thrust loads.
- Spherical-roller thrust bearing
  - Useful where heavy loads and misalignment occur.
  - The spherical elements have the advantage of increasing their contact area as the load is increased.
- Needle bearings
  - Useful where radial space is limited.
  - High load capacity
- Tapered roller bearings
  - Combine the advantages of ball and straight roller bearings.
  - High load-carrying capacity



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Bearing Life

A stochastic variable with both a distribution and associated statistical parameters.

- Common measures of Bearing Life
  - Number of revolutions of the inner ring (outer ring stationary) until the first tangible evidence of fatigue
  - Number of hours of use at a standard angular speed until the first tangible evidence of fatigue
- The life measure of an individual bearing
  - The total number of revolutions (or hours at a constant speed) of bearing operation until the failure criterion is developed.
- Failure criterion
  - Under ideal conditions, the fatigue failure consists of spalling of the load-carrying surfaces.
  - The spalling or pitting of an area of 0.01 in^2 (Timken Company)
- Rating Life (*Minimum life*, L_{10} *life*, and B_{10} *life*)
  - The number of revolutions (or hours at a constant speed) that 90 percent of a group of bearings will achieve or exceed before the failure criterion develops.
  - 10^{th} percentile location of the bearing group's revolutions-to-failure distribution
  - Median Life (50^{th} percentile), between 4~5 times the L_{10} *life*.

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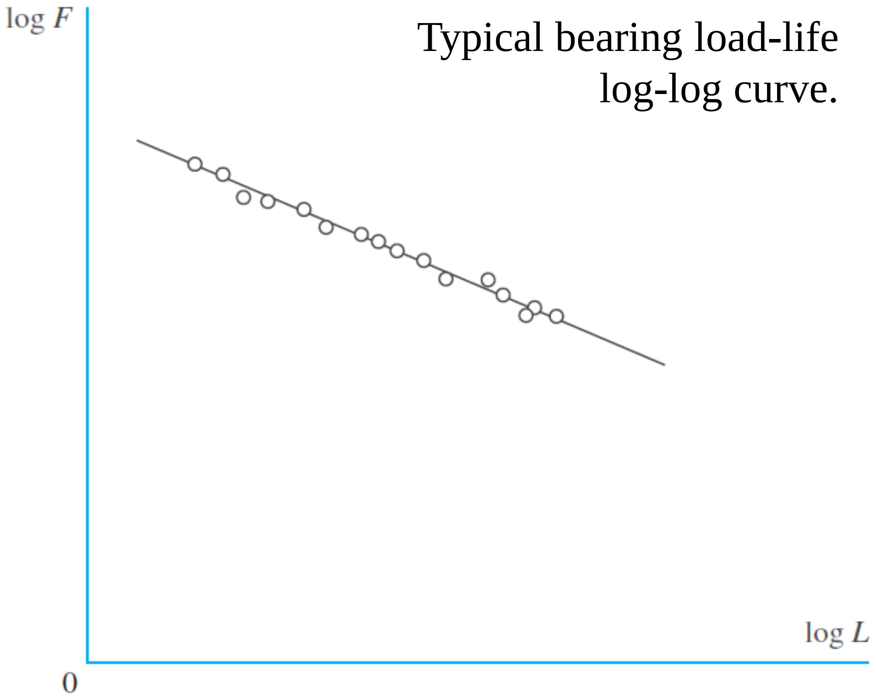
Bearing Load Life at Rated Reliability

What the manufacturing says vs. how long the bearings actually last

- To establish a single point, **load F_1** and the **rating life of group one $(L_{10})_1$** are the coordinates that are logarithmically transformed.
- The **reliability** associated with this point, and all other points, is 0.90.
- Catalog load rating (C_{10})
  - the radial load that causes 10 percent of a group of bearings to fail **at the bearing manufacturer's rating life**.



Typical bearing load-life log-log curve.

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

- $a = 3$ for ball bearings
- $a = 10/3$ for roller bearings

Relate the *Desired* to the *Published*

How to select a bearing for a given application?

The units of L_R and L_D are revolutions

$$F_R L_R^{1/a} = F_D L_D^{1/a}$$

The subscripts *R* and *D* stand for Rated and Desired.

Life *L* in revolutions, £ is in hours, *n* is in rev/min

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

60 min/h is the appropriate conversion factor.

$$F_R(\mathscr{L}_R n_R 60)^{1/a} = F_D(\mathscr{L}_D n_D 60)^{1/a}$$

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

$$C_{10} = F_R = F_D\left(\frac{L_D}{L_R}\right)^{1/a} = F_D\left(\frac{\mathscr{L}_D n_D 60}{\mathscr{L}_R n_R 60}\right)^{1/a}$$

Catalog load rating as a function of the desired load, desired life, and catalog rating life.

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Reliability versus Life

At constant load, the life measure distribution of rolling-contact bearings is right skewed.

- Three-parameter Weibull distribution
  - Robust ability to adjust to varying amounts of skewness
  - Used exclusively for expressing the reliability of rolling-contact bearings
- Reliability, *R*, for a Weibull distribution of the life measure

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

x_0 = guaranteed, or "minimum," value of x

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

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

  - The life measure is expressed in dimensionless form as $x=L/L_{10}$.
- Given a specific required reliability, one can estimate life measure *x*.

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

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Relating Load, Life, and Reliability

A designer's problem

- What is desired (by the designer) is different from what is listed (by the manufacturer), so a compromise (decision) has to be made by the design engineer based on <u>an expected reliability</u>.

A: The catalog information, the logs of C_{10} and $x_{10}=L_{10}/L_{10}=1$, a point on the 0.90 reliability contour.

D: The design point, a point on a desired reliability contour, $R=R_D$.

Moving from D through B to A.

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

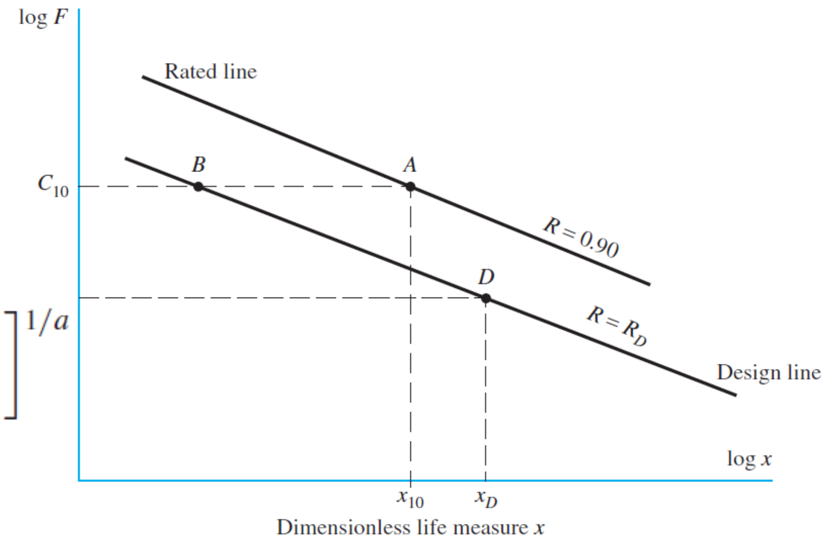
$$R_D = \exp\left[-\left(\frac{x_B - x_0}{\theta - x_0}\right)^b\right]$$

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

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

an application factor a_f

$$C_{10} \approx a_f F_D\left[\frac{x_D}{x_0 + (\theta - x_0)(1 - R_D)^{1/b}}\right]^{1/a} \quad R \geq 0.90$$



Convert from a design situation with a desired load, life, and reliability to a catalog load rating based on a rating life at 90 percent reliability.

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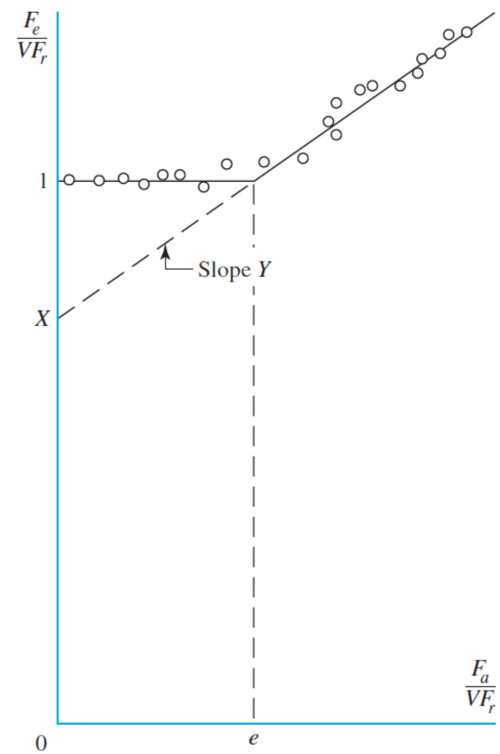
Combined Radial and Thrust Loading

A ball bearing is capable of resisting radial loading and a thrust loading, or combined.

- F_e to be the ***equivalent radial load*** that does the same damage as the combined radial (F_r) and thrust (F_a) 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.
  - For the case of ball bearing
- Two dimensionless groups can be plotted.
  - $F_e / (VF_r)$ and $F_a / (VF_r)$
  - The abscissa e is the intersection
- Expression $F_e = X_i V F_r + Y_i F_a$
  - where i = 1 when $F_e / (VF_r) \leq e$
  - and i = 2 when $F_a / (VF_r) > e$.



$$\frac{F_e}{VF_r} = 1 \qquad \text{when } \frac{F_a}{VF_r} \leq e$$

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

Equivalent Radial Load Factors for Ball Bearings

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

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

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

Notes on Bearing Selection

What's available from the manufacturer's handbook?

- Such information has been accumulated the hard way, that is, by experience.
- The beginner designer should utilize this information until he or she gains enough experience to know when deviations are possible.

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

Bearing-Life Recommendations for Various Classes of Machinery

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

Load-Application Factors, same purpose as the factors of safety.

Example on Bearing Life Estimation

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 $\mathscr{L}_{10}$ life at a speed of 720 rev/min.

$$V = 1 \text{ and } F_a/C_0 = 400/4450 = 0.090.$$

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

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

$$F_a/(VF_r) = 400/[(1)500] = 0.8 > 0.285.$$

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

With $\mathscr{L}_D = \mathscr{L}_{10}$ and $F_D = F_e$,

$$\mathscr{L}_{10} = \frac{60\mathscr{L}_R n_R}{60 n_D}\left(\frac{C_{10}}{F_e}\right)^a = \frac{10^6}{60(720)}\left(\frac{7900}{890.8}\right)^3 = 16\,150 \text{ h}$$

Lubrication

The contacting surfaces in rolling bearings have a relative motion that is both rolling and sliding, so it is difficult to understand exactly what happens.

- The purposes of an antifriction-bearing lubricant:
  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

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

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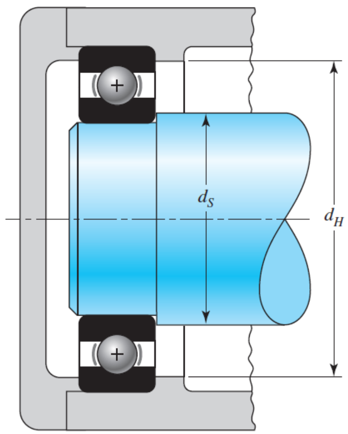
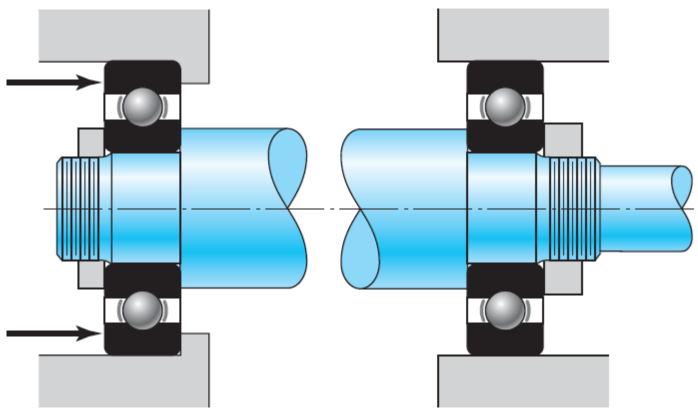
Mounting and Enclosure

Each new design is a real challenge to the ingenuity of the designer.

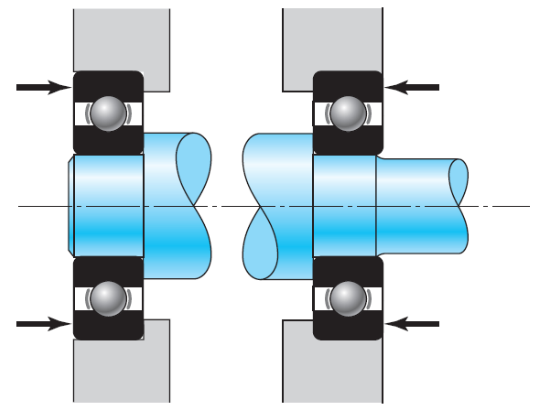
- Each operation contributes to the cost of production, so that the designer, in ferreting out a trouble-free and low-cost mounting, is faced with a difficult and important problem

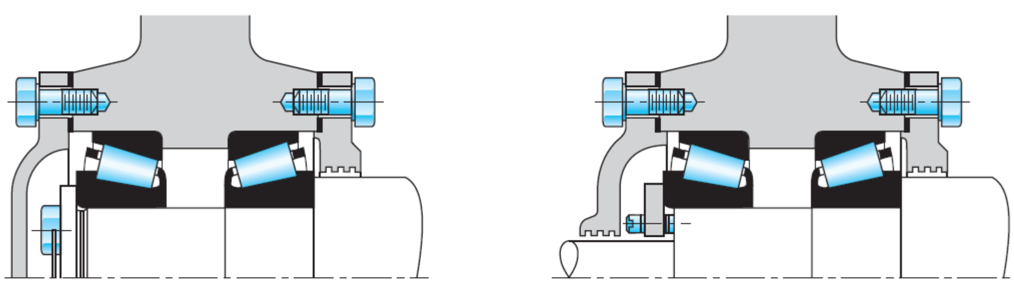


Common Bearing Mounting



Another Common Bearing Mounting

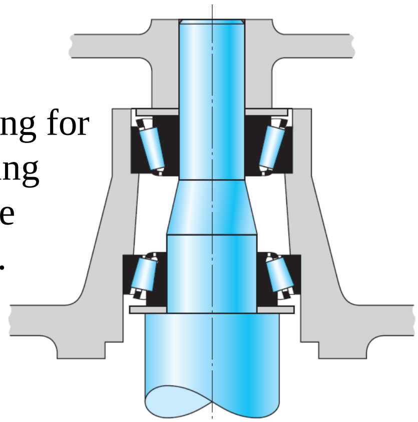




(a) (b)

Two-bearing mountings.

Mounting for a washing machine spindle.



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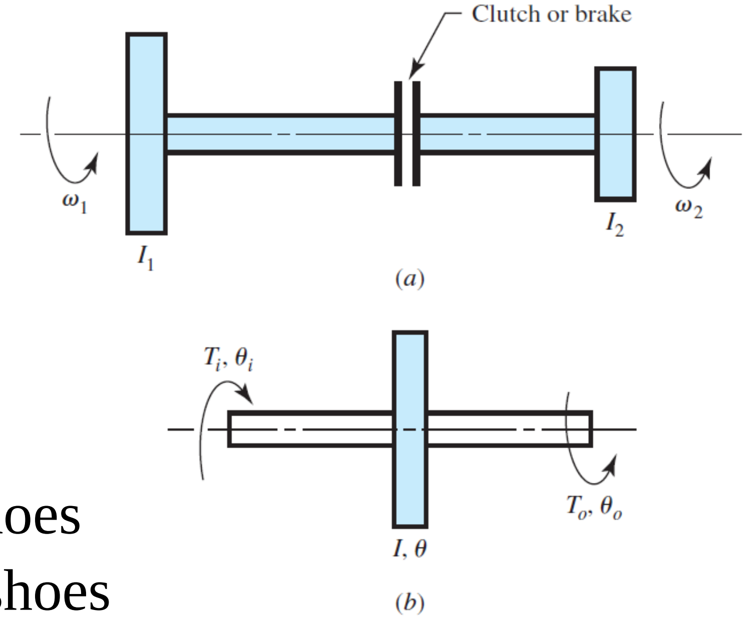
Clutches, Brakes, Couplings, and Flywheels

Rotary elements with the function of storing and/or transferring rotational energy.

- Interest of analysis
  - The actuating force
  - The torque transmitted
  - The energy loss
  - The temperature rise
- Types
  - Rim types with internal expanding shoes
  - Rim types with external contracting shoes
  - Band types
  - Disk or axial types
  - Cone types
  - Miscellaneous types



A flywheel is an inertial energy-storage device. It absorbs mechanical energy by increasing its angular velocity and delivers energy by decreasing its velocity.

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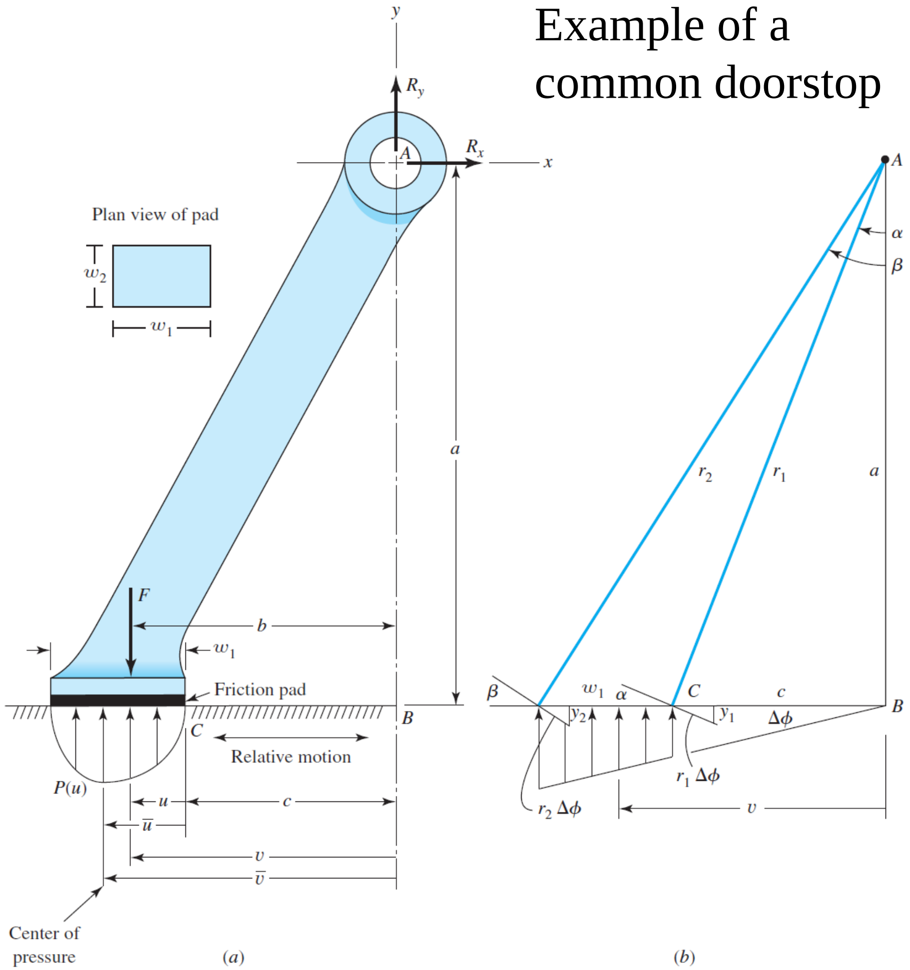
Static Analysis of Clutches and Brakes

Similar Procedure of Analysis

- Estimate, model, or measure the pressure distribution on the friction surfaces.
- Find a relationship between the largest pressure and the pressure at any point.
- Use the conditions of static equilibrium to find the braking force or torque and the support reactions.

Example of a common doorstop



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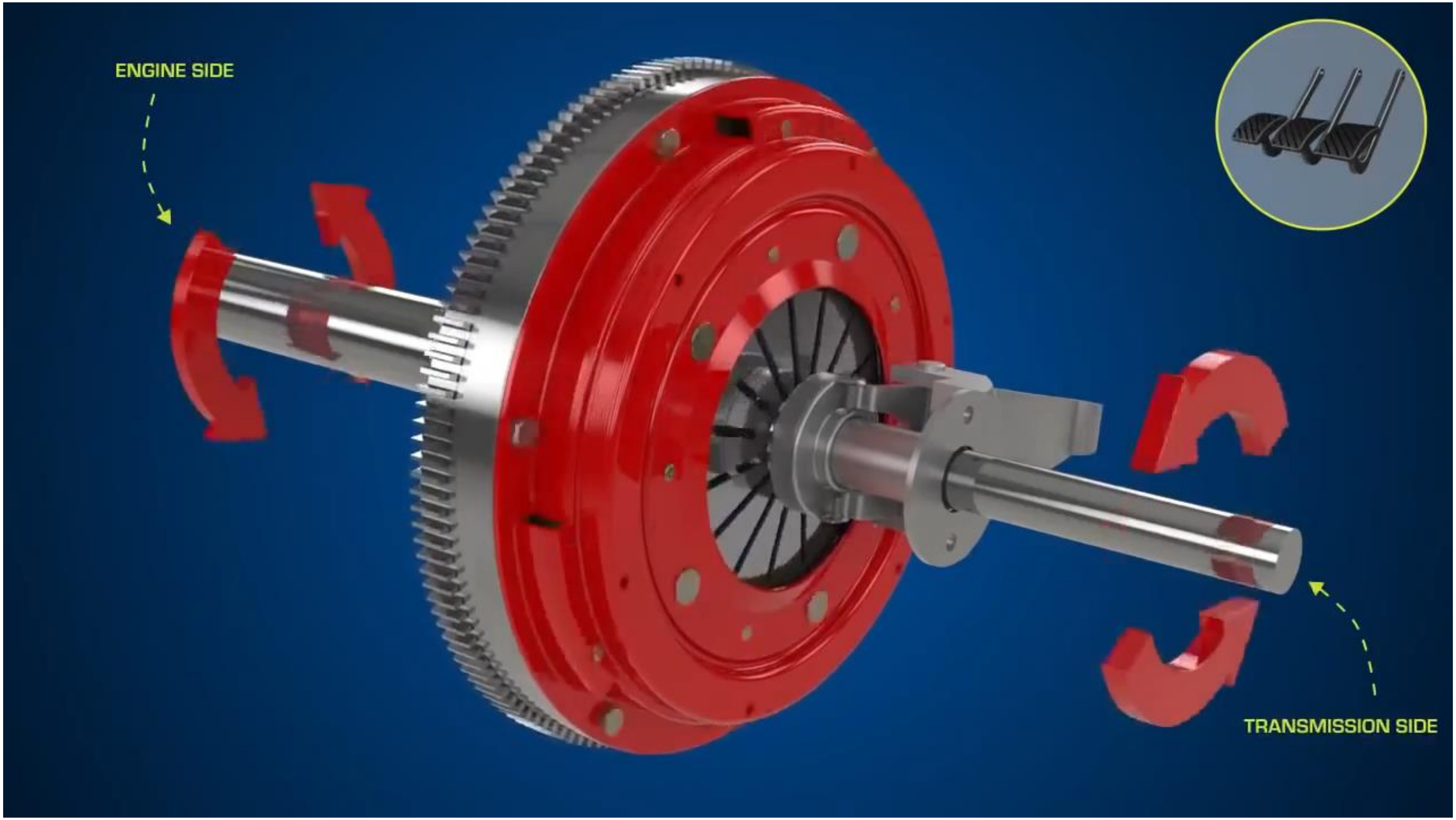
How A Clutch Works?

https://www.youtube.com/watch?v=pqF-aBtTBnY



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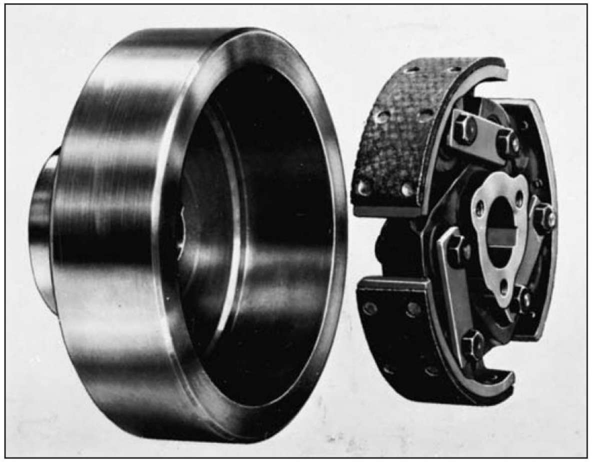
Internal Expanding Rim Clutches and Brakes

- Three essential elements
  - the mating frictional surface,
  - the means of transmitting the torque to and from the surfaces,
  - and the actuating mechanism.



- Clutch classification based on operating mechanism
  - Expanding-ring
    - often used in textile machinery, excavators, and machine tools where the clutch may be located within the driving pulley
  - Centrifugal
    - used mostly for automatic operation
  - Magnetic
    - particularly useful for automatic and remote-control systems
  - Hydraulic & Pneumatic
    - useful in drives having complex loading cycles and in automatic machinery, or in robots

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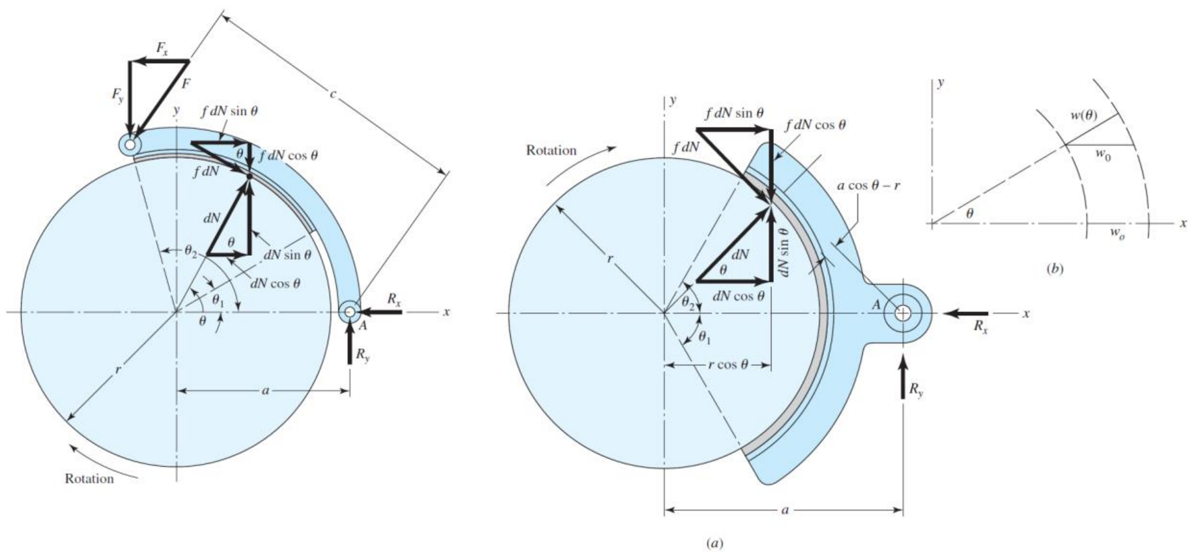
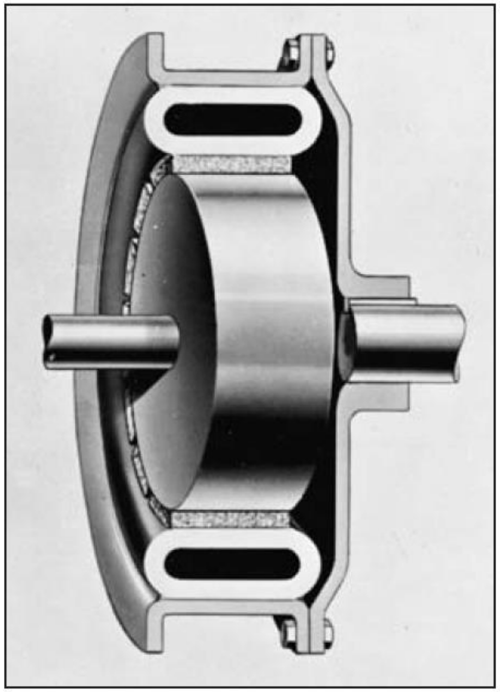
External Contracting Rim Clutches and Brakes

- Operating mechanisms can be classified as
  - Solenoids
  - Levers, linkages, or toggle devices
  - Linkages with spring loading
  - Hydraulic and pneumatic devices



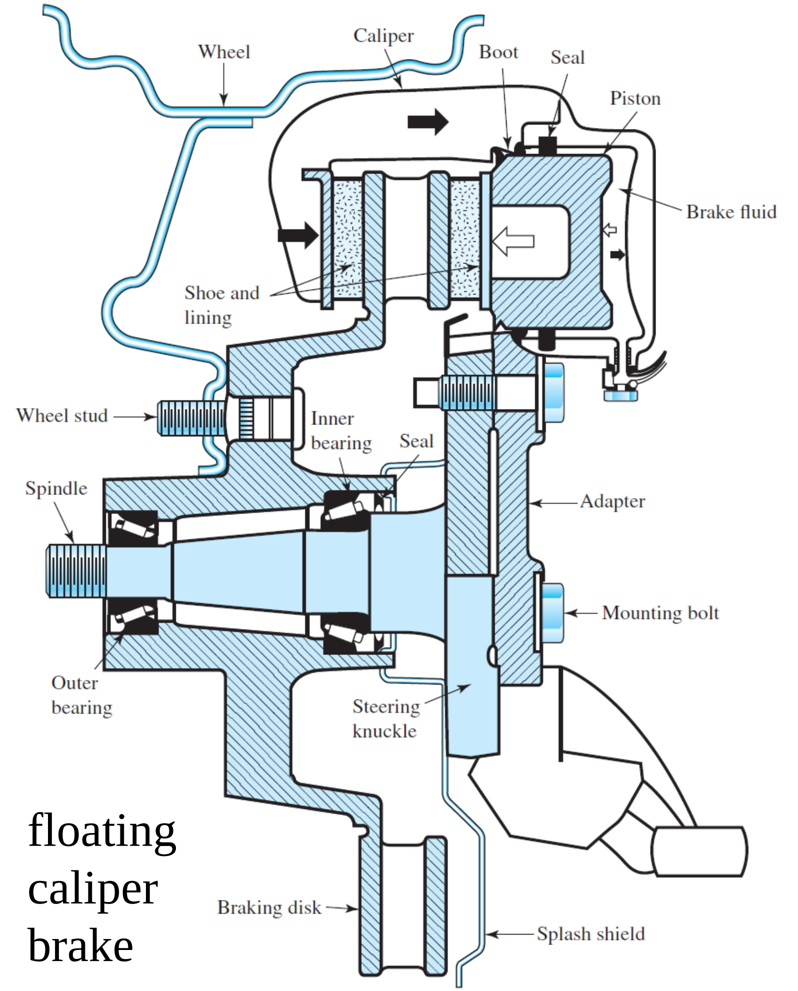


An external contracting clutch-brake that is engaged by expanding the flexible tube with compressed air.

Disk Brakes

No fundamental difference between a disk clutch and a disk brake

- The caliper supports a single floating piston actuated by hydraulic pressure.
- Caliper brakes (named for the nature of the actuating linkage) and disk brakes (named for the shape of the unlined surface) press friction material against the face(s) of a rotating disk.



floating caliper brake

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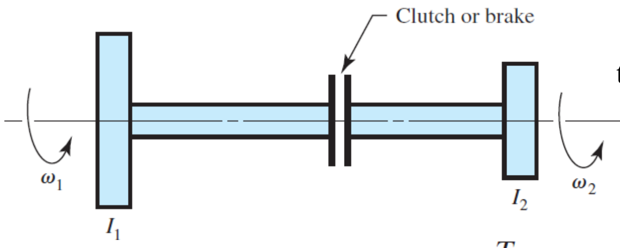
Energy Considerations

the amount of heat generated by a clutching or braking operation

- Heat generation
  - When the rotating members of a machine are caused to stop by means of a brake, the kinetic energy of rotation must be absorbed by the brake.
  - When the members of a machine that are initially at rest are brought up to speed, slipping must occur in the clutch until the driven members have the same speed as the driver.
- The character of the load may be such that, if this torque value is permitted, the clutch or brake may be destroyed by its own generated heat.
  - the characteristics of the material
  - the ability of the clutch to dissipate heat



We assume that the two shafts are rigid and that the clutch torque is constant.

$$I_1\ddot{\theta}_1 = -T \qquad \dot{\theta} = \dot{\theta}_1 - \dot{\theta}_2 = -\frac{T}{I_1}t + \omega_1 - \left(\frac{T}{I_2}t + \omega_2\right)$$

$$I_2\ddot{\theta}_2 = T \qquad = \omega_1 - \omega_2 - T\left(\frac{I_1 + I_2}{I_1 I_2}\right)t$$

Let the time required for the entire operation be t_1.

$$\dot{\theta} = 0 \text{ when } \dot{\theta}_1 = \dot{\theta}_2, \qquad t_1 = \frac{I_1 I_2(\omega_1 - \omega_2)}{T(I_1 + I_2)}$$

$$u = T\dot{\theta} = T\left[\omega_1 - \omega_2 - T\left(\frac{I_1 + I_2}{I_1 I_2}\right)t\right]$$

$$E = \int_0^{t_1} u\,dt = T\int_0^{t_1}\left[\omega_1 - \omega_2 - T\left(\frac{I_1 + I_2}{I_1 I_2}\right)t\right]dt = \frac{I_1 I_2(\omega_1 - \omega_2)^2}{2(I_1 + I_2)}$$

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Friction Materials

The manufacture of friction materials is a highly specialized process, and it is advisable to consult manufacturers' catalogs and handbooks, as well as manufacturers directly, in selecting friction materials for specific applications.

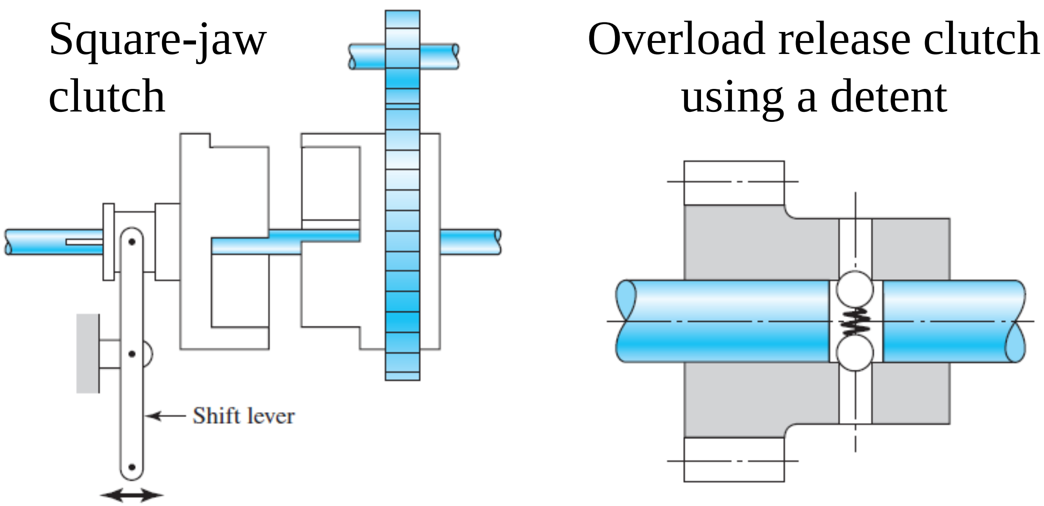
- High and reproducible coefficient of friction
- Imperviousness to environmental conditions, such as moisture
- The ability to withstand high temperatures, together with good thermal conductivity and diffusivity, as well as high specific heat capacity
- Good resiliency
- High resistance to wear, scoring, and galling
- Compatible with the environment
- Flexibility

Material	Friction Coefficient f	Maximum Pressure p_{max}, psi	Maximum Temperature Instantaneous, °F	Maximum Temperature Continuous, °F	Maximum Velocity V_{max}, ft/min	Applications
Cermet	0.32	150	1500	750		Brakes and clutches
Sintered metal (dry)	0.29–0.33	300–400	930–1020	570–660	3600	Clutches and caliper disk brakes
Sintered metal (wet)	0.06–0.08	500	930	570	3600	Clutches
Rigid molded asbestos (dry)	0.35–0.41	100	660–750	350	3600	Drum brakes and clutches
Rigid molded asbestos (wet)	0.06	300	660	350	3600	Industrial clutches
Rigid molded asbestos pads	0.31–0.49	750	930–1380	440–660	4800	Disk brakes
Rigid molded nonasbestos	0.33–0.63	100–150		500–750	4800–7500	Clutches and brakes
Semirigid molded asbestos	0.37–0.41	100	660	300	3600	Clutches and brakes
Flexible molded asbestos	0.39–0.45	100	660–750	300–350	3600	Clutches and brakes
Wound asbestos yarn and wire	0.38	100	660	300	3600	Vehicle clutches
Woven asbestos yarn and wire	0.38	100	500	260	3600	Industrial clutches and brakes
Woven cotton	0.47	100	230	170	3600	Industrial clutches and brakes
Resilient paper (wet)	0.09–0.15	400	300		$PV < 500\ 000$ psi · ft/min	Clutches and transmission bands

Characteristics of Friction Materials for Brakes and Clutches

Miscellaneous Clutches and Couplings

- Design Considerations
  - They do not slip.
  - No heat is generated.
  - They cannot be engaged at high speeds.
  - Sometimes they cannot be engaged when both shafts are at rest.
  - Engagement at any speed is accompanied by shock.
- The greatest differences among the various types of positive clutches are concerned with the design of the jaws.



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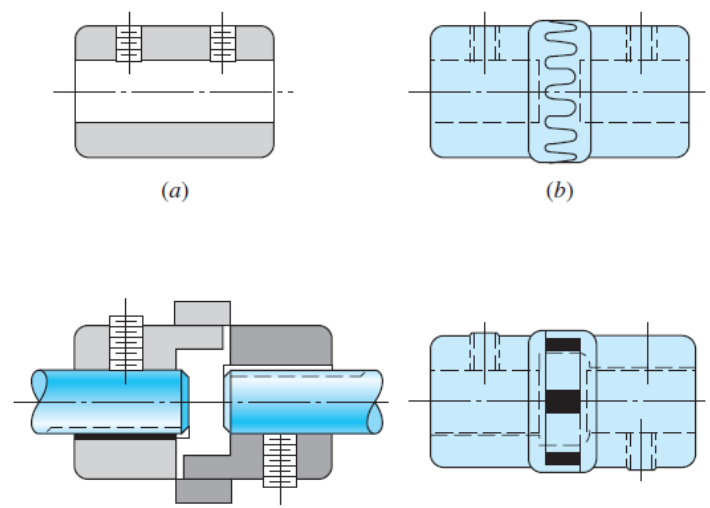

(c) (d)

Project 3: Shaft Design

- Online at course website

Next class

- **Lab for Group 1**: Design Consultation
- Friday 0800-1000, Nov 29
- Room 412, 5 Wisdom Valley

- **Discussion for Group 2**: Design Consultation
- Friday 0800-1000, Nov 29
- Room 202, 1 Lychee Park

Thank you!

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