Precision Machine Design

Topic 15

Rolling element bearings for rotary motion

Purpose:

Rotary motion ball bearings are one of the most commonly used, and important, types of bearings. During WWII, bearing plants were prime targets, because without rolling element bearings, the wheels of war would grind to a halt - literally. This lecture begins our discussion of the design and use of ball bearings.

Outline:

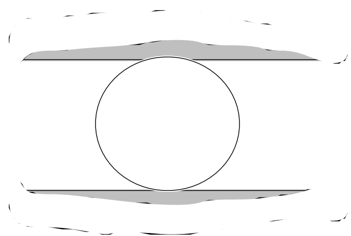
- **General characteristics**
- **Bearing types**
- **Thermocentric design**

"Never tell people how to do things. Tell them what to do and they will surprise you with their ingenuity."

General G. S. Patton

Speed and acceleration limits:

- **Centrifugal force expands the outer race and increases the contact stress between the balls and the outer race..**
- **Viscous shear in the lubricant and imperfect rolling contact cause the entire bearing to thermally expand.**
  - **Hertzian deformation means that the bearing is making contact at a range of different radii!**



- **The outer race usually is attached to a bigger heat sink so it tends to expand less.**
  - **A back-to-back bearing configuration is used to maintain stability.**
- **When the line of contact is not aligned with the angular acceleration vector (e.g., angular contact bearings):**
  - **At high speeds, gyroscopic forces cause the ball to spin.**
  - **At high speeds, a cooling and lubricating oil mist is often required:**
    - **Oil mist requires clean, dry (<100 ppm) air.**
    - **This air quality is the same as is required for air bearings.**
    - **An alternative is to use oil directed at the rolling element contact surface via holes in the inner race.**

- **Bearing speed is limited by its DN value, where D is the diameter in mm and N is the allowable rpm.**
  - **Shear power is the product of velocity (Rw) and force ($R\omega\mu A/h$) or $(R\omega)^2\mu A/h$**
  - **Centrifugal load is proportional to $r\omega^2$**
- **Typical DN sped values** (Courtesy of The Torrington Company.)**:**

Bearing Type	Type of Cage	ABEC-1 Grease (1)	ABEC-1 Oil (2)	ABEC-3 Grease (1)	ABEC-3 Oil (2)	ABEC-7 Grease (selected)	ABEC-7 Circulating oil	ABEC-7 Oil mist
Single row, non-filling slot type	Molded nylon PRB	200,000	250,000	200,000	250,000	250,000	250,000	250,000
	pressed-steel	250,000	300,000	250,000	300,000	300,000	350,000	400,000
Single row filling slot type	Molded nylon PRB	200,000	200,000	-	-	-	-	-
	pressed-steel	200,000	250,000	-	-	-	-	-
Radial and angular -contact single row	Molded nylon PRC composite CR (ring piloted)	300,000	350,000	300,000	400,000	400,000	600,000	750,000
Angular-contact single and double row	Molded nylon PRB	200,000	250,000	-	-	-	-	-
	pressed-steel	200,000	250,000	-	-	-	-	-
Single row angular-contact	Metallic (ring-piloted)	250,000	300,000	-	-	-	-	-

(1) Grease filled to 30 to 50% of capacity. Type of grease must be carefully chosen to achieve the above speed values. Consult Fafnir for complete recommendations.
(2) For oil bath lubrication, oil level should be maintained between 1/3 to 1/2 from the bottom of the lowest ball.

- **Much higher values can be obtained with ceramic components (DN to 2 million) and higher grade bearings (ABEC 9).**

- **Acceleration limits are usually not quoted because speed usually dominates the selection criteria.**
    - **High accelerations cause damage if the bearing elements slip which enhances wear.**
    - **A tractive fluid[1] can also be used as a lubricant to prevent slip in bearings with high accelerations.**
- **In general, as speed increases**
    - **Life decreases**
    - **Cost increases**
    - **Productivity increases**
    - **Machine cost increases (axes must go faster too)**
- **All these must be considered to create a machine that increases Return On Investment (ROI).**

[1] e.g., Monsanto's Santotrac™

Applied loads:

- **Many rolling element bearings can support radial and axial loads.**

- **In order to size a rotary motion bearing, an equivalent radial load F_e must be found:**

$$F_e = K_\omega K_r F_r + K_A F_A$$

  - **K_ω: rotation factor = 1 for rotating inner ring and 2 for a rotating outer ring.**

  - **K_r: radial load factor = 1 (almost always).**

  - **K_A: axial load factor.**

- **A typical load life equation for rolling element bearings has the form:**

$$L_a = a_1 a_2 a_3 (C/F_e)^\gamma$$

  - **L_a: millions of revolutions.**
  - **a_1: 1.0 for a 10% probability of failure[2].**
  - **a_2: a materials factor which is typically 3.0 for steel bearings .**
  - **a_3: lubrication factor, which typically is 1.0 for oil mist.**
  - **C: basic dynamic load rating from a table of available bearings.**
  - **F_e: the applied equivalent radial load, determined by bearing type.**
  - **γ: 3 for balls and $^{10}/_3$ for rollers.**

  - **For high speed applications:**

    - **The operating speed must be taken into account when calculating the equivalent radial load.**

  - **Precision life is about 90% of the L_{10} life**

2 This is referred to as the L10 life. Be careful how failure is defined. In most cases it means the machine grinds to a halt, but accuracy can be lost long before that.

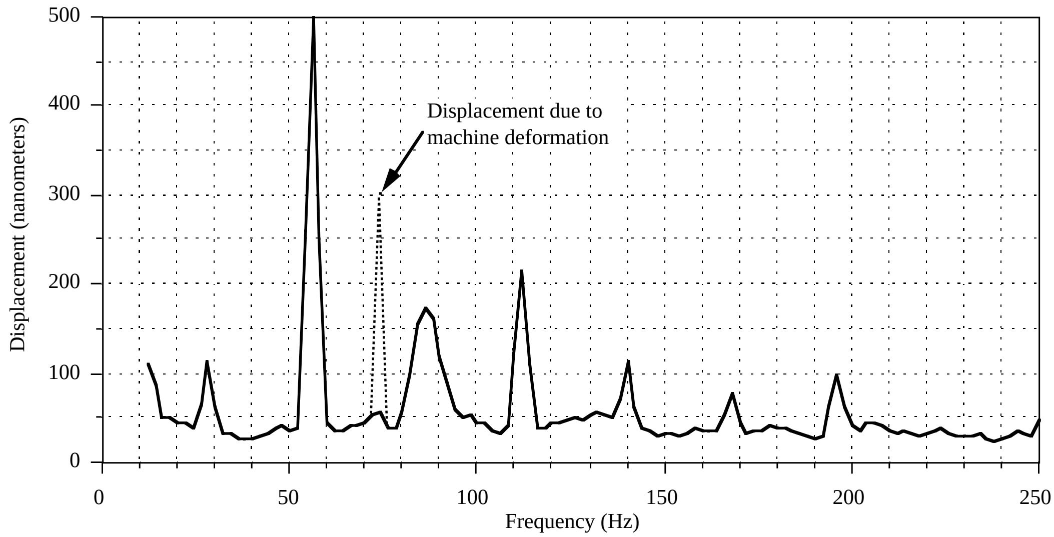
Accuracy:

- **Accuracy of the first kind (error motions) is defined here in terms of axis of rotation errors (See Chapter 2).**
- **Accuracy of the second kind is defined here as:**
    - **The position accuracy which the bearing will allow the component it supports to be servoed.**
  - **The accuracy to which the bearing components are made which is represented by the ABEC number**
    - **Bearings used in appliances are usually ABEC 1.**
    - **Bearings used in many machine tools are ABEC 5.**
    - **Precision spindles use ABEC 7 or 9 bearings.**

- **In addition to the ABEC number, the accuracy of a rolling element bearing primarily depends upon:**
  - **The accuracy of the machine component onto which it is mounted, and the mounting method.**
  - **The number of rolling elements.**
  - **Bearing stiffness.**
  - **Operating speed.**
  - **Non-sphericity of rolling elements caused by preload.**
  - **Lubricant viscosity which is affected by contact pressure.**
    - ***Elastohydrodynamic lubrication* layer:**
      - **Lubricant is dragged into the contact region.**
      - **Viscosity increases with pressure.**
      - **Lubricating film is maintained.**

- **Vibration from rolling elements may affect the overall accuracy of the machine.**

- **Typical frequency spectrum of a rolling element bearing spindle's radial error motion:**



- **The spindle speed was 1680 rpm (28 Hz).**

- **Principal detective tools are the error motion analyzer and the FFT of the error motion!**

- **The elements in a rolling element rotary motion bearing generate error motions whose frequency can be predicted.**
- **For inner and outer ring speeds ω_i and ω_o, respectively in rpm, the *rotation frequency* is:**

$$f_i = \frac{\omega_i}{60}$$

$$f_o = \frac{\omega_0}{60}$$

- **Most often either ω_i or ω_o is zero.**
- **A bearing ring will never be perfectly round.**
- **To obtain the primary error motion frequency:**
    - **Equation 8.3.6 must be multiplied by the number of lobes (e.g., 2 for an egg shape).**

- **As the rolling elements roll, they move the cage along with them.**
- **This assembly revolves about the bearing's rotation axis with a speed of ω_c, which generates errors at the *cage frequency*:**

$$f_c = \frac{\omega_c}{60} = \frac{1}{60\, D_{pitch}} \left(\frac{D_{pitch} - D_{ball} \cos\beta}{2}\, \omega_i + \frac{D_{pitch} + D_{ball} \cos\beta}{2}\, \omega_o \right)$$

- **β is the ball-groove contact angle and the pitch diameter is usually the average of the bore and outside diameter.**
- **The frequency of the error motion caused by the rolling elements themselves is the *rolling element frequency*:**

$$f_b = \frac{\omega_b}{60} = \frac{1}{60\, D_{ball} \cos\beta} \left(\frac{D_{pitch} - D_{ball} \cos\beta}{2}\, \omega_i - \frac{D_{pitch} + D_{ball} \cos\beta}{2}\, \omega_o \right)$$

- **The *inner race frequency* and *outer race frequency* are, respectively:**

$$f_{ir} = \left| f_i - f_c \right| N$$

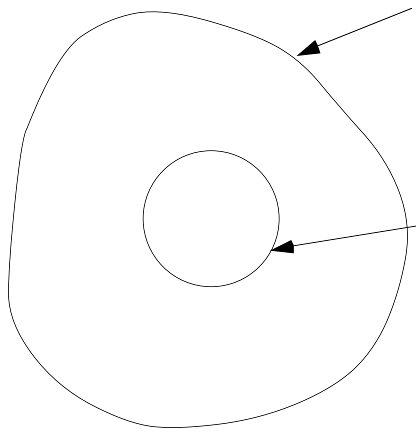
$$f_{or} = \left| f_o - f_c \right| N$$

- **N is the number of rolling elements.**
- **In a spindle that has many sets of bearings, one is not even sure of the relative phase between the bearings:**
  - **The above frequencies may beat in very unusual ways.**
- **Professional Instruments[3] makes a bearing analyzer which measures bearings before they are mounted.**
  - **The output is the ANSI error motion plots and the FFTs of the error motions.**

[3] Contact Steve Sanner, Professional Instruments Corp., 7800 Powell Road, Hopkins, MN 55343; phone (612) 933-1222, fax (612) 933-3315.

Repeatability:

- **Ideally, rolling contact bearings do not require a wear in period.**
- **In practice, an assembly is run for several days to insure that components seat properly and failure doesn't occur.**
- **Bearing manufacturers often simply refer to the radial error motion as "total non-repetitive runout":**
  - **This is now not a standard term.**
- **The Total Indicated Runout (TIR) is 2X the total radial error motion (bearing and artifact errors), and the artifact mounting eccentricity.**
  - **It is the max. difference in output from a sensor measuring radial motion.**

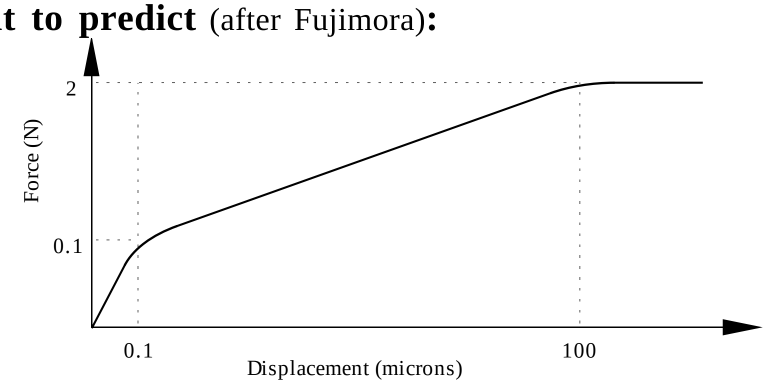


- **A precision ball bearing spindle may have a total radial error motion on the order of 1/4 - 1/2 μm (1/2 - 1 μm TIR).**
- **Spindle error analyzers are commercially available.**[4]

[4] Contact Don Martin at Don Martin, Lion Precision, 7685 Washington Ave South Minneapolis , MN 55435-2705, phone (612) 484 6824, fax (612) 484 6544, or Dr. Kam Lau at API phone (301) 948-7986. Federal Products now also makes a spindle analyzer.

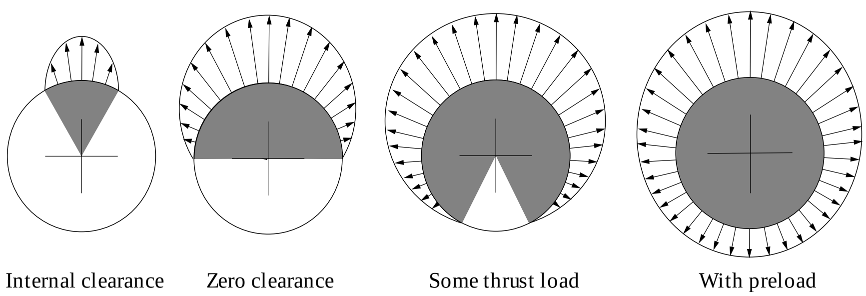
Resolution

- **The ability of the bearing to roll and allow small motions of the components it supports.**
  - **Difficult to quote figures for bearing resolution because of the great dependency on the rest of the machine.**
  - **The higher the preload, the poorer the resolution is likely to be.**
  - **A good indicator of the resolution is the starting torque or force required to begin motion.**
- **For rotary motion precision ball bearings, resolution can be from microradians to nanoradians.**
  - **For very small motions the rolling element acts as a flexural bearing and angstrom resolution is possible.**
  - **As soon as the element begins to roll:**
    - **A large decrease in performance will be seen with respect to nanoscale performance.**
  - **On the mrad range of motion scale, the resolution will appear to be smooth once again.**
  - **The transition from flexing to rolling is probably very difficult to predict** (after Fujimora)**:**



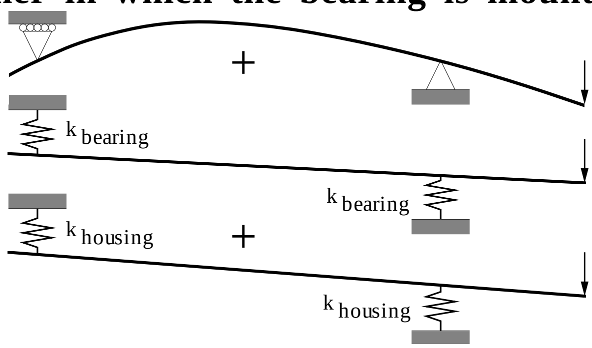
Preload

- **Preload greatly affects all aspects of bearing performance, often a very nonlinear way.**
- **Stiffness increases continually with preload.**
- **Accuracy and repeatability increase with preload as the bearing gap is closed.**
    - **They then decrease as friction levels begin to increase.**
- **Resolution almost always decreases with increasing preload.**
- **Preload is achieved by:**
    - **Displacing one race axially with respect to the other.**
    - **Expanding or contracting the inner or outer race on a taper.**
    - **Loading the bearing with oversize balls or rollers.**
- **Effect of bearing preload on the region of the bearing that effectively acts to support the load** (Courtesy of The Timken Co.)**:**

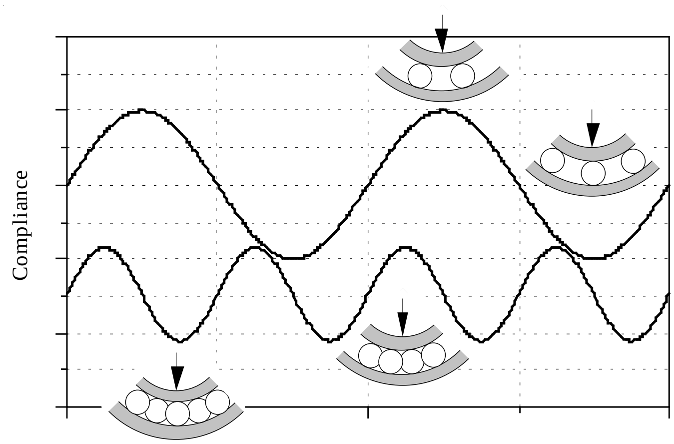


Stiffness

- **Nonlinear and depends on:**
  - **The number and type of rolling elements.**
  - **The shape of the raceways.**
  - **The preload force.**
  - **The manner in which the bearing is mounted:**



- **Illustrative comparison of the compliances of single- and double-row bearings:**



Vibration and shock resistance

- **The contact area is small: be careful to maintain adequate preload when vibration or shock loads are present.**
  - **Preload increases the contact area.**
  - **If the unpreloaded rolling element is separated from the race by a substantial fluid layer:**
    - **The fluid layer directly between the rolling element and the race is incompressible.**
    - **It is driven into the race like a needle, leaving a conical depression.**
- **Rolling elements' small contact areas means damping will primarily be due to that of the materials.**
- **Take care to ensure that the bearing is not subject to vibration during long periods when it is not moving.**
    - **Vibration without rolling causes the rolling elements to work their way through the lubricating layer.**
    - **Metallic contact can be made with the race.**
    - **With steel bearing components, this can lead to fretting corrosion and premature failure.**
    - **Stainless steel or ceramic components resist fretting corrosion.**

Damping

- **Low radially and axially due to small contact areas.**
- **Low along direction of motion.**

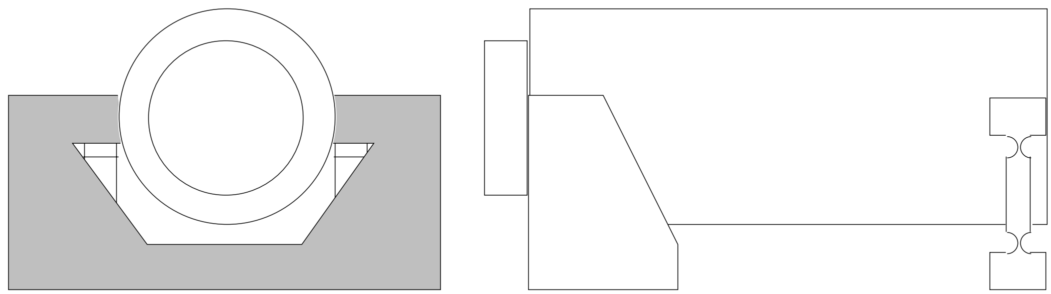
Friction

- **With increasing preload, the static coefficient of friction may increase from a low of about 0.001 to about 0.01.**
  - **Rolling elements become less round.**
- **The quoted breakaway torque can be an indicator of bearing performance.**
- **A bearing under load will behave quite differently then an unloaded bearing.**
- **The dynamic coefficient of friction of rolling contact bearings may be on the order of 0.001-0.01.**
- **The dynamic coefficient of friction can change if the lubricant's viscosity changes with temperature.**
- **Very closely related to resolution!**

Thermal performance:

- Significant amounts of heat (lubricant, preload, and bearing-type dependent) can be generated at high speed.
  - Heat can cause expansion and a decrease in accuracy (thermal growth).
    - Using thermocouples *mounted to the bearing outer rings* allows thermal errors to be mapped and reduced by an order of magnitude.
  - Heat can cause expansion and overloading of the bearings.
- Frictional properties will also generally change with load and speed which affects rate of heat generation.
- The interdependence of this relation makes modeling bearing thermal performance difficult but not impossible.
- Computer aided bearing design packages can help answer questions such as:
  - How much oil (or grease) to use?
  - Must the oil be cooled?
  - What oil (or grease) viscosity to use?
  - How much cooling is required?
  - What is the operating temperature?
- In general, one should isolate the heat sources, cool them, and use thermally insensitive designs.

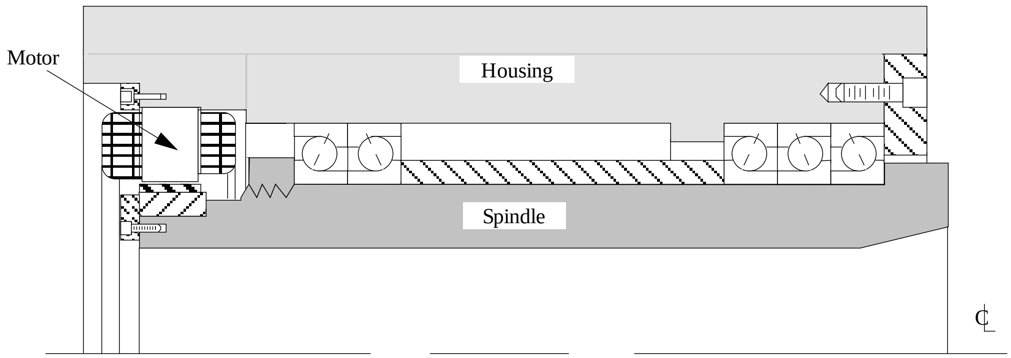
- **Design Strategy: use neutrally supported components and control the temperature of the supports.**
- **This way, thermal growth doesn't greatly affect the centerline location of the component, or axial growth** (Design by Dave Youden of Rank Taylor Hobson)



- **The flexures may have to be insulated to control their thermal time constant.**
- **This prevents the spindle from suffering from thermal pitch errors.**

- **Mounting strategies to prevent overconstraint in the presence of thermal growth:**

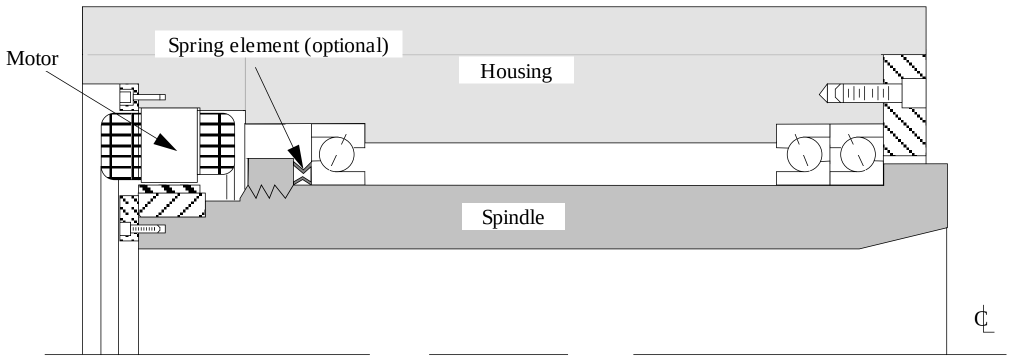
  1. Let one set of bearings be free to slide in the bore:



  - **This is the most common, least expensive, and least desirable method.**
  - **It can lead to decreased radial stiffness and accuracy if the fit is too loose.**
  - **Early bearing failure if the fit is too tight.**
  - **Consider using a surface treatment in the bore to decrease friction.**

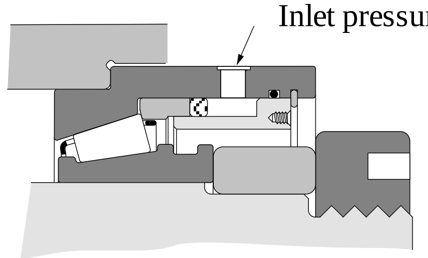
- **Once you build a good spindle, to repeat the process, measure and record:**
  - **Measured starting torque**
  - **Static and dynamic stiffness**
  - **Error motions**
  - **Temperature as a function of speed and time**

2. Preload sets of bearings to yield a thermocentric design:



- **The radial and axial spacing are set so thermal growths cancel each other.**
- **Optionally, a spring element is used to preload the system to allow for deviations from ideal growth.**
- **This is a very difficult configuration to design and thus is not often used for a multi-purpose spindle.**

3. Use a hydraulic device to maintain a fixed preload on the bearings (Hydra-Rib™).

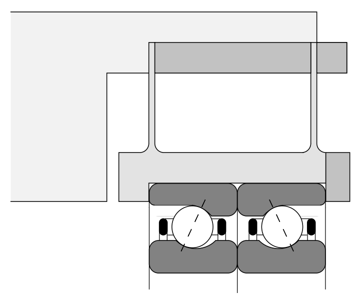


- **This is an effective, but more expensive, method.**

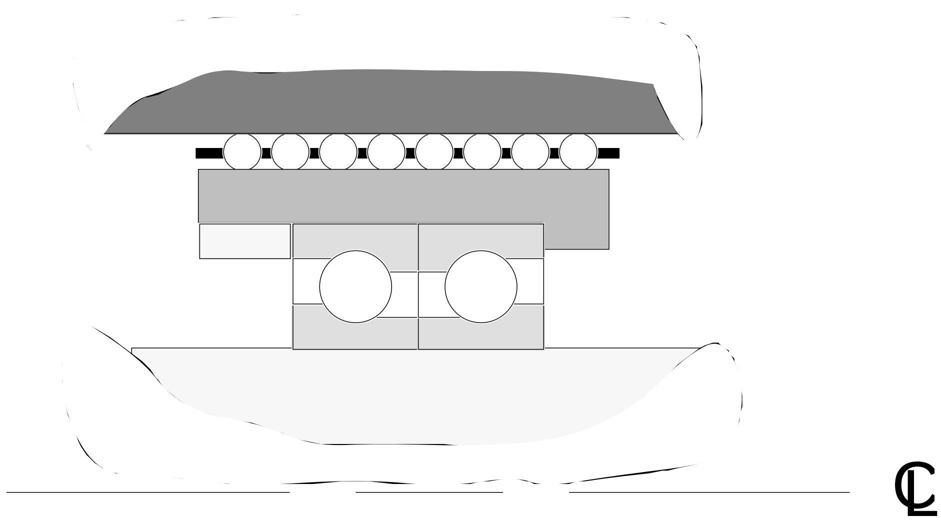
4. Use a straight roller bearing as the rear support bearing.

5. Use a diaphragm flexure to support the bearing set which must have freedom to move axially.

- **This is a moderate cost method that does require extra room and thus is not often used.**
- **Method for bearing mounting that provides:**
- **Good radial stiffness.**
- **Low axial stiffness.**
- **Accomodation of axial thermal growth of the supported shaft.**



6. Use a die-set bushing as a micro-motion flexural rolling element bearing:



7. Use angular contact bearings in the front, and straight or holler roller bearings in the rear.

Environmental sensitivity

- **Extremely sensitive to dirt.**
- **Bearings can themselves generate micro wear particles.**
- **Typically, no matter what the application, rolling element bearings require some sort of seal.**

Seal-ability

- **Rotary motion rolling element bearings are relatively easy to seal using labyrinth, wiper, or screw-thread type seals.**
- **At high speeds, non-contact seals (Hydra Seals) are required to avoid heat generation.**
- **High pressure coolant bouncing off of a part can force its way past non-contact.**

Size and configuration

- **The number of types and sizes of rolling element bearings is almost innumerable.**
- **If you can imagine it, a bearing manufacturer probably can or does make it.**
- **Don't be shy or too hastily think you've invented the wheel.**

Weight

- **Weight is generally not a concern with rolling element bearings used in earth based precision machines.**

Support equipment

- **Sealed lubricated for life ball bearings are available that do not need any support equipment.**
- **Some spindle bearings need a temperature controlled oil supply/return system.**
- **Oil-mist systems require clean, dry (<100 ppm H_2O) air that actually is the same quality used by air bearings.**
- **Injection of oil through the inner race and onto the bearing requires a special high-speed coupling through the rear of the shaft.**

Maintenance requirements

- **Oil cooled bearings require scheduled maintenance to change filters and check the oil.**
- **Air filters and dryers for oil mist systems must be carefully maintained.**

Material compatibility:

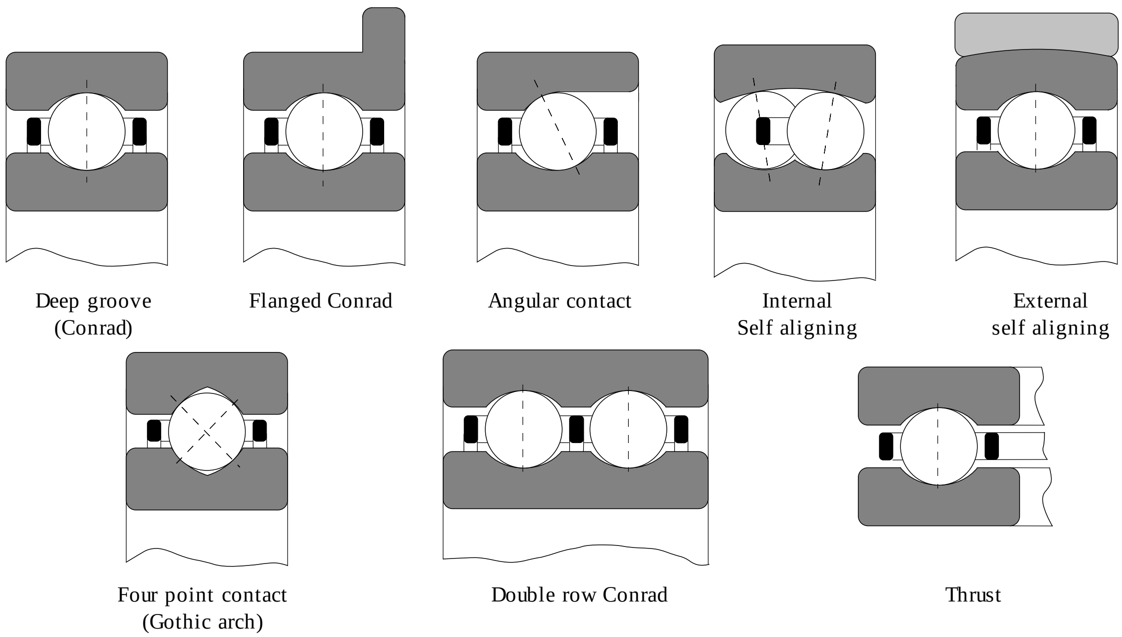
- One can always find suitable materials for use in virtually any environment.
- For intermittent motion, beware of fretting corrosion.

Required life

- Properly designed, manufactured, installed, and maintained:
    - Rolling element bearings can provide tens of millions of cycles of trouble free accurate motion.
    - Assumes proper mounting including manufacturing tolerances.
    - Some wear will occur with every cycle:
    - Elastic preloading compensates for some geometry change.
- The greatest unknowns are contamination getting by the seals, and impact loading.

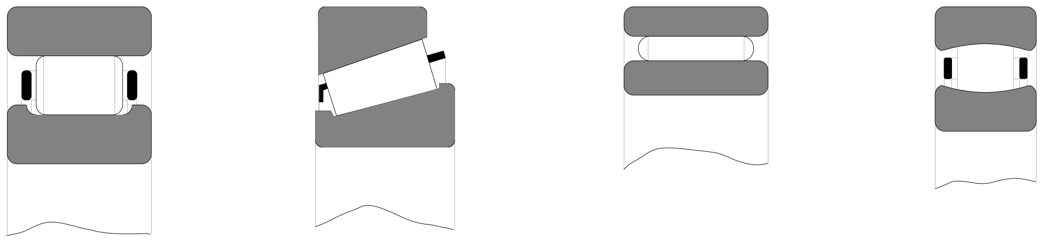
Bearing types

- **Typical ball bearing configurations for rotary motion bearings:**



- **Load capacity and stiffness depends on:**
  - **Radius of curvature of the ball and groove.**
  - **Ball-groove contact angle.**
  - **Number of balls.**
- **Typically, the inner race is radially displaced and the balls are loaded from one side.**
- **The balls are distributed around the race and their spacing is then maintained by the retainer (cage).**
- **Full compliment bearings have a filling slot, no cage, high load capacity, and limited speed.**

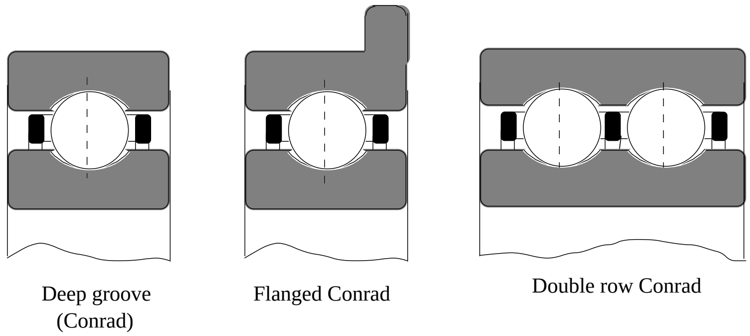
- **Typical roller bearing configurations for rotary motion bearings:**



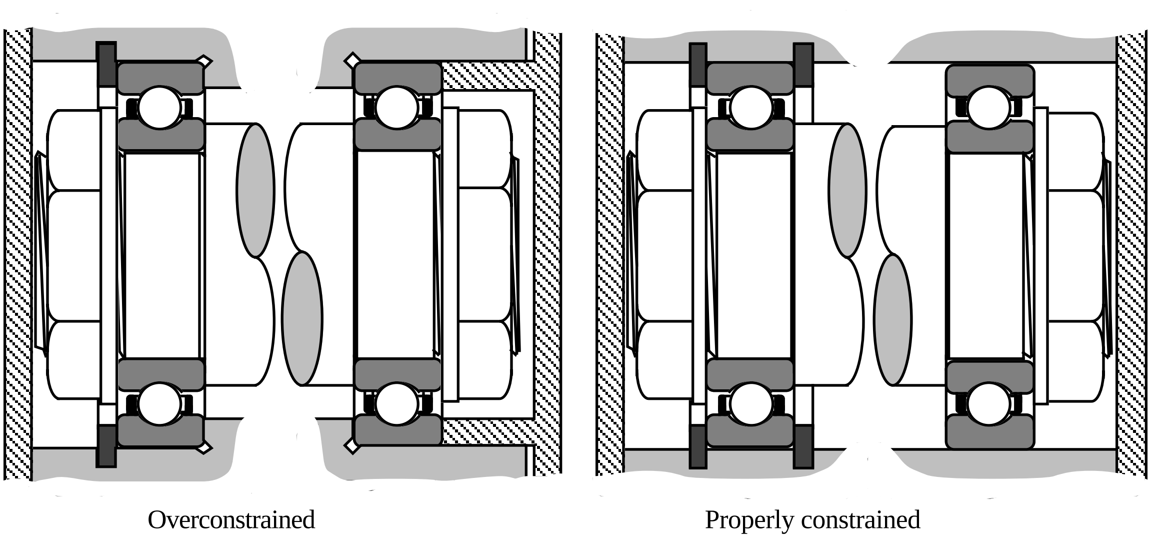
Straight roller Tapered roller Needle Spherical roller

- **Roller bearings can be loaded with very high packing density.**
- **A cage is required primarily to keep the rollers from rubbing against each other as they roll.**
- **Since the rollers are ideally in line contact, roller bearings generally have very high load capacity and stiffness.**

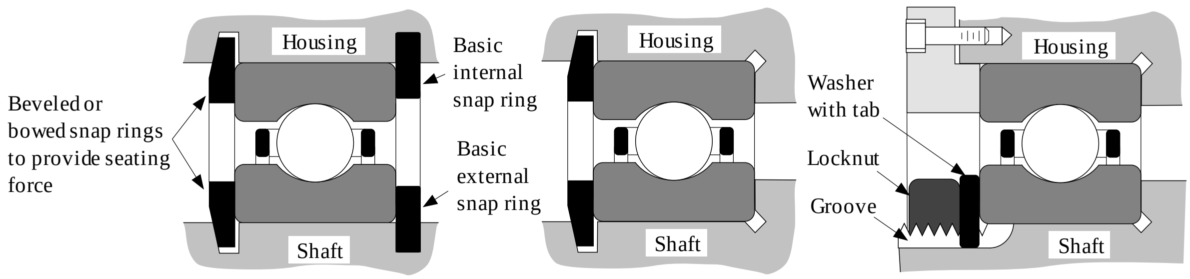
Deep groove bearings



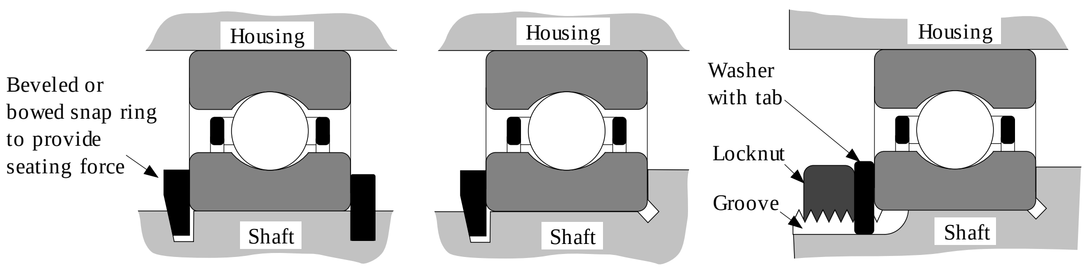
- **Small radius of curvature deep groove (*Conrad*) bearing:**
  - **The most commonly manufactured bearing and are widely used in consumer products and industrial equipment.**
  - **Groove radius of curvature is close to that of the balls.**
  - **Large axial and radial load capacity.**
  - **Preloaded through the use of oversize balls.**
  - **One bearing's non-rotating ring is usually allowed to float axially unrestrained:**



- **Methods for mounting Conrad bearings with full axial restraint in a bore and on a shaft:**



- **Methods for mounting Conrad bearings with full axial restraint on a shaft and axial freedom in a bore:**



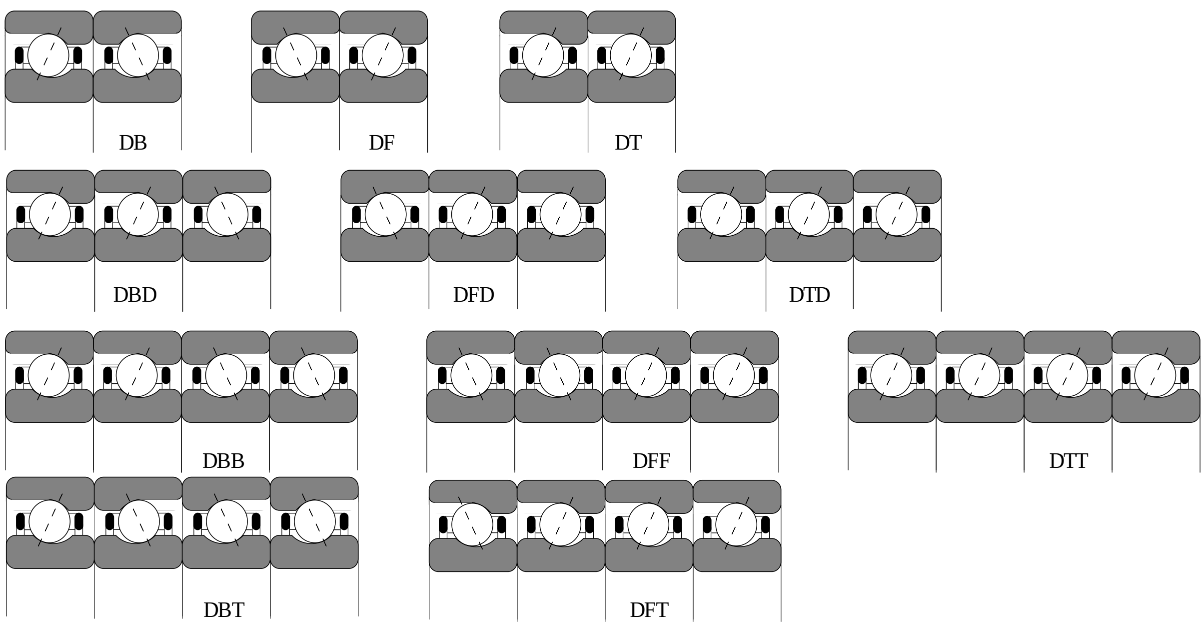
- **Exercise extreme caution when using a bolted flange to press against a bearing race:**
  - **Unless the bolts are placed close enough and the flange is think enough (so cones of influence overlap):**
    - **The bolt forces can apply effective point forces on the race and cause a poisson expansion.**
    - **This creates a "bump" on the race which the balls have to roll over.**
    - **Bearing noise and errors can increase significantly.**

- **Radial and axial error motion:**
    - **Total radial error motion of radial contact bearings can be on the order of 1/2-1 μm for high precision grades.**
    - **Axial error motion may be large (a few μm) because of the ideally pure radial contact.**
    - **Conrad bearings can be assembled in a back-to-back configuration to obtain reasonable axial performance.**
    - **For high speed, high accuracy applications, one would probably use angular contact bearings.**
- **Radial, thrust, and moment load support capability:**
    - **Large radius of curvature shallow groove bearings have low to moderate radial load capacity and low axial load capability.**
    - **Deep groove radial contact bearings have high radial load capacity and moderate axial load capability.**
    - **Moment loads are resisted by using pairs of radial contact bearings that are spaced suitably far apart.**
    - **Double row bearings or sets of match ground bearings can be used to increase load capacity.**
    - **Double row bearings' balls can be one-half pitch apart.**
        - **This can reduce sinusoidal variation in radial stiffness as the balls roll by up to 70%.**
        - **Angular contact bearings can also be obtained in double row configurations.**

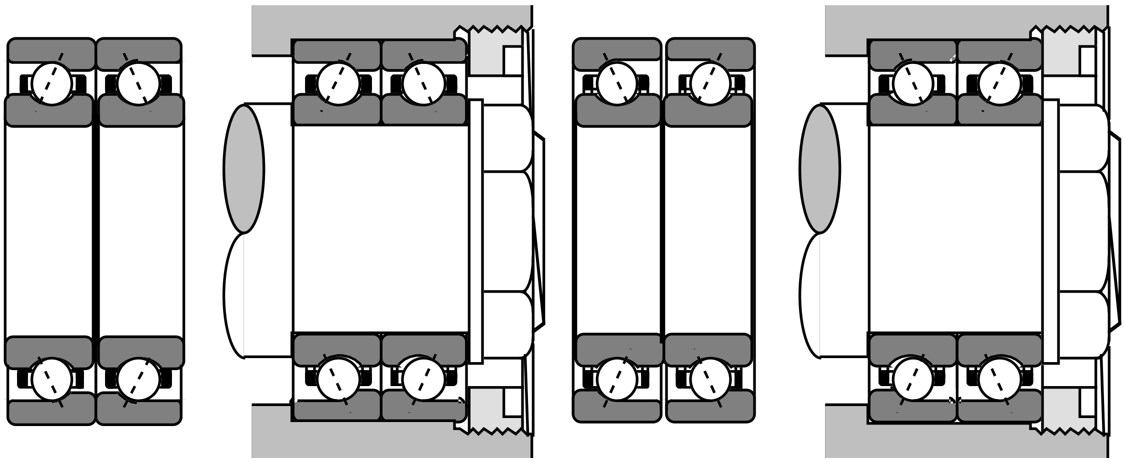
- **Allowance for thermal growth:**
  - **Bearings generate heat when rotating.**
    - **The housing usually has much better heat transfer to the outside world than the shaft.**
  - **Bearings must be mounted to allow the shaft to expand axially without placing axial loads on the bearings.**
- **Alignment:**
  - **Radial contact bearings are more forgiving of misalignment than other non-self aligning ball bearings.**
  - **Typical allowance for nonparallelity of the shaft to bore centerline may be as high as 1 mm/m.**
- **Preload adjustment:**
  - **No preload mechanism required. Preload is obtained with the use of slightly oversize balls.**
  - **Conrad bearings can be assembled in a back-to-back configuration to obtain reasonable axial performance.**

Angular contact bearings

- **Balls contact the races along a line inclined to a plane orthogonal to the axis of rotation.**
- **Radial load capacity and thrust load capacity in one direction are high.**
- **In order to support bidirectional thrust loads, a second bearing facing the opposite way is needed.**
- **To attain high stiffness and load capacity:**
  - **Two, three, or four (or more) bearings can be used forming Duplex, Triplex, or Quadruplex sets:**



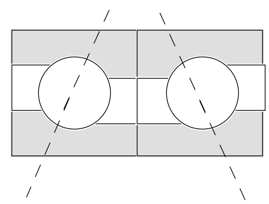
- **To preload angular contact bearings against each other, they can be mounted back to back or face to face:**



Before mounting — Back-to-back mounting after inner rings are clamped together — Before mounting — Face-to-face mounting after outer rings are clamped together

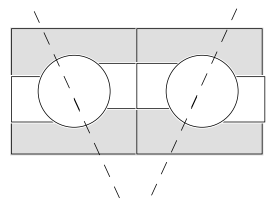
- **Preload adjustment:**
  - **Angular contact bearings are usually used in pairs.**
    - **Preloaded by clamping the races until the overhung surfaces are forced together as shown earlier.**
  - **Press fitting the races into a bore or onto a shaft causes the width of the races to change (the Poisson effect):**
    - **Take care to follow manufacturer's recommendations.**
  - **Avoid using angular contact bearings which require the user to measure axial spacing.**
    - **Then grind and insert shims to control preload.**
    - **This method is inaccurate and a source of quality control nightmares.**

- **The amount of relative overhang in the races determines the amount of preload.**
- **Bearings are available flush ground or with a moderate amount of overhang (preload obtained after assembly).**
- **In the back-to-back mode:**



  - **The lines of force action project away from each other and give the pair a high moment resisting capability.**
  - **The bearings are less tolerant of misalignment.**
  - **For a fixed outer race, the shaft expands axially and radially more than the housing.**
    - **The preload remains relatively constant.**

- **In the face-to-face mode:**



  - **The moment stiffness is low (greater misalignment tolerance).**
  - **The bearings are more tolerant of misalignment.**
  - **The system is thermally unstable for a rotating inner race.**
    - **Differential radial and axial growth both tend to increase the preload.**
- **When the outer race is rotating and the inner race is fixed, the face-to-face configuration may be more thermally stable.**

Radial and axial error motion

- **Total axial and radial error motions can be as low as 1/4 μm but typically are on the order of 1/2-1 μm.**
- **Commercially available spindles, are available with total error motions (TIR/2) of 1/4 - 1/2 μm.**
- **Angular contact bearings typically have three times the speed capability of radial contact bearings.**
- **Angular contact bearings are generally the most often used type of ball bearing in precision machinery.**

Radial, thrust, and moment load support capability

- **Radial load capability is about the same as for a similar size Conrad bearing.**
- **Angular contact bearings can support up to three times the thrust load of a Conrad bearing.**
- **A radial force loads only one side of the ring whereas an axial force loads the entire ring.**
- **The resultant thrust force from a radial force on one of the bearings:**
  - **Does not appreciably change the equivalent radial load on the other bearing.**
- **When radial loads are applied to a back-to-back or face-to-face mounting, the axial force components cancel.**
- **When a thrust load is applied, it only "flows" through the bearing whose contact angle faces it.**
  - **It acts to unload the other bearing.**

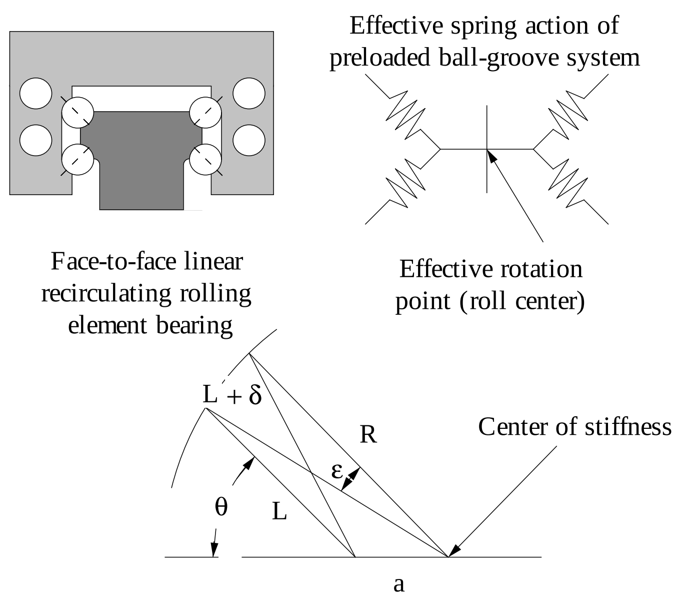
Allowance for thermal growth

- **One must axially and radially restrain bearing sets on one end of the shaft.**
- **Generally only radially restrain bearing sets on the other end of the shaft.**
- **Only when speeds are low and relative shaft and bore thermal expansions negligible:**
    - **Should a front bearing be preloaded against the rear bearing.**
    - **Unless a careful thermocentric design analysis is done.**

Alignment

- **A single angular contact bearing can tolerate a misalignment of about ± 2' (0.5 mm/m).**
- **A duplex pair acts to resist moment loads.**
    - **It has an alignment tolerance of essentially zero degrees with another pair used to support a long shaft.**
- **When using sets of angular contact bearings at each end of a shaft (e.g., a spindle):**
    - **Extreme care must be taken to ensure that the bore centerlines are coincident.**
    - **The surfaces the races mate with, at each end of the shaft, must be concentric.**

Why face-to-face mountings have a large angular misalignment capability:



- **The bearing rotates about an effective center:**
  - **When it is subject to an applied moment.**
  - **When an enforced condition of geometric congruence.**

- **To determine the forces in the balls associated with this misalignment:**
  - **The effective elongation (compression) of the preloaded balls must be determined.**
- **This can be done starting with the law of cosines:**

$$R^2 = L^2 + a^2 - 2La\cos(180 - \theta)$$
$$= L^2 + a^2 + 2La\cos(\theta)$$

- **After the rotation takes place:**

$$R^2 = (L + \delta)^2 + a^2 + 2La\cos(\theta + \varepsilon)$$

- **The displacements δ and θ are small, so with small angle approximations:**

$$\delta = a\,\varepsilon\,\sin\theta$$

- **For a face-to-face arrangement of bearings, θ is acute ($\cos\theta$ is positive) and *a* is small.**
  - **Thus δ is small and $F = k\delta$, so F on balls is small.**
- **For a back-to-back arrangement, θ is obtuse ($\cos\theta$ is negative), and *a* is large.**
- **Thus for a fixed displacement (misalignment):**

$$\delta_{back\text{-}to\text{-}back} > \delta_{face\text{-}to\text{-}face}$$

- **Force in a spring is proportional to the displacement.**
- **Hence the face-to-face bearing is subject to lower stresses when it is misaligned.**

Straight roller & needle bearings

- **Due to line contact, they can support very high loads and have very high stiffness.**
- **Often used to support heavily loaded shafts that are axially constrained by tapered roller or angular contact bearings.**
  - **E.g. a roll used in steel making or printing, or a heavy duty spindle.**
- **Needle bearings are long thin rollers.**
  - **Used in applications where space is at a premium and high load carrying capability is required.**
  - **E.g. automotive driveshafts.**
  - **The lack of a cage (separator) limits their speed.**

Radial and axial error motion

- **Straight rollers can be individually inspected and cylindrical races easily ground and inspected.**
- **Very small (0.5 μm) radial and axial total error motions can be obtained.**

Radial, thrust, and moment load support capability

- **Ideally used only to support radial loads.**
- **When used in conjunction with other bearings to form a couple:**
  - **Straight roller bearings can support very large moment loads.**
- **The inner and outer races must both be axially restrained on the shaft and in the bore respectively.**

Allowance for thermal growth

- **Not meant to resist axial loads.**
- **Differential radial expansion between the bore and the shaft must not change bearing preload.**

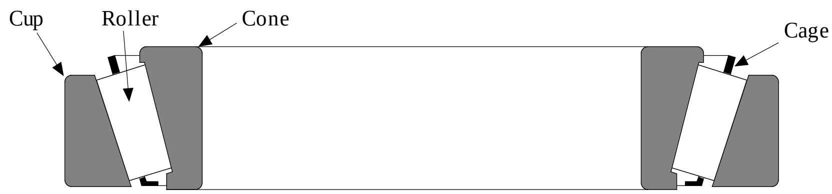
Alignment

- **Shaft misalignment causes the rollers to be compressed into tapered shapes.**
- **Increases wear and friction and the tendency to migrate axially.**
- **Alignment must be within about 10-100 μm/m.**

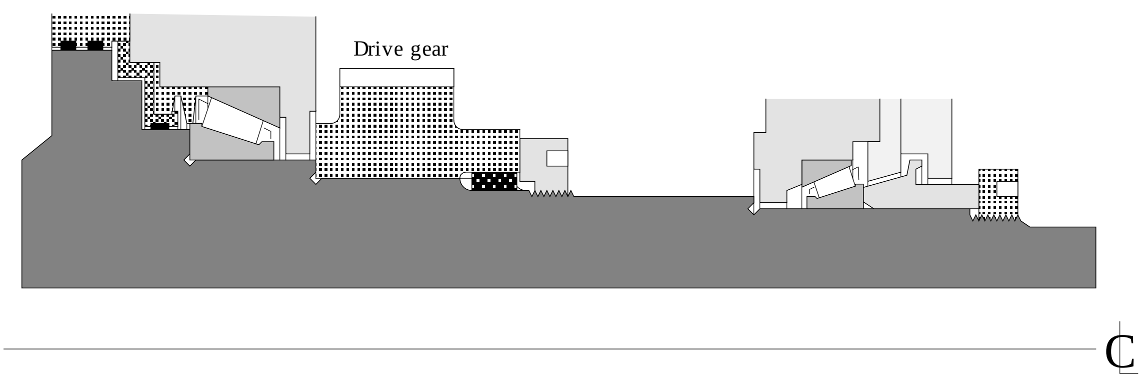
Preload adjustment

- **Preloaded by using oversize rolling elements.**
- **Using a bearing with a slight taper on the inner race inside diameter.**
    - **The taper rides on a mating taper on the shaft and preload is set during assembly.**

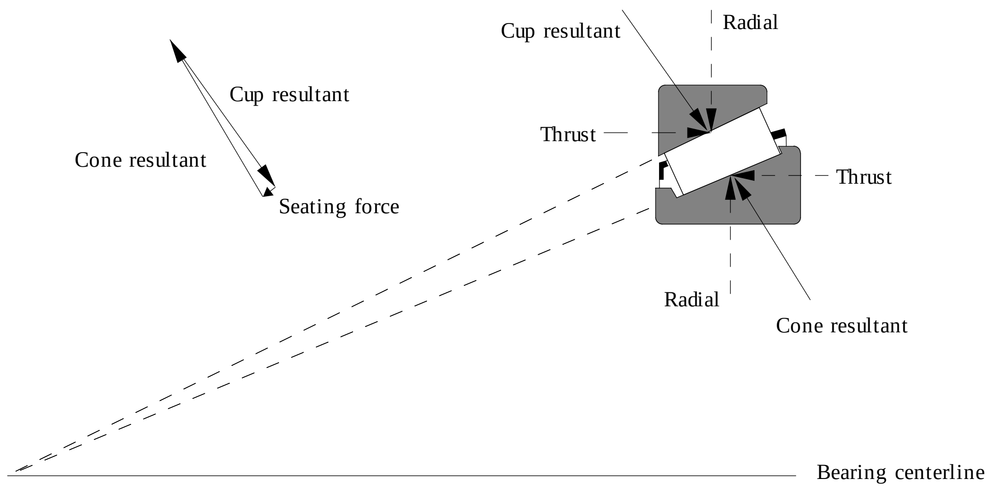
Tapered roller bearings



- **Wide range of applications from supporting the axles in a car to supporting heavy duty machine tool spindles:**
- **Like angular contact bearings they are meant to be used in pairs with one bearing preloaded against the other.**
- **Tapered roller bearings in a precision 37.5 kW (50 hp) turning center spindle (drawing not to scale)** (Courtesy of The Timken Co.)**:**



- **The lines tangent to the raceway and roller surfaces meet at a common point on the axis of rotation.**
- **Hence true rolling motion of the tapered roller is attained** (Courtesy of The Timken Co.)**:**



- **Like angular contact bearings, tapered roller bearings' rolling elements are also subject to gyroscopic forces.**

Radial and axial error motion

- **It is more difficult to finish a tapered cylindrical surface than a spherical one:**
  - **Tapered roller bearings cannot match the dimensional performance of an angular contact ball bearing.**
  - **Angular contact bearings cannot match the load capcity and stiffness of tapered roller bearings.**
- **For machine tool applications:**
  - **Radial and axial total error motions on the order of 0.5-1.0 μm can be obtained (AAA & AA bearings).**
- **Typical tapered roller bearing 2X total radial error motion** (Courtesy of The Timken Co.)**:**

Cup OD		Class			
Over (mm)	Including (mm)	C (μm)	B (μm)	A (μm)	AA (μm)
30	50	6	2.5	2	1
50	120	6	3.5	2	1
120	150	7	3.5	2	1
150	180	8	4	2	1
180	250	10	5	2	-
250	266.7	11	5	2	-
266.7	315	11	5	-	-

Radial, thrust, and moment load support capability

- **Line contact exists between the rollers and races:**
  - **They have very high stiffness and can support very high axial and thrust loads.**
- **The contact forces between the roller and raceway are not parallel, so the effect is to squeeze the roller out.**
- **This causes the flat end of the roller which is orthogonal to the cone axis to seat on a lip on the inner race.**
- **This helps keep the rollers from skewing but adds to the friction coefficient of the bearing.**
- **Tapered roller bearings can be mounted back-to-back or face-to-face just like angular contact ball bearings.**
- **Sets of tapered roller bearings are also often grouped at each end of a shaft:**
  - **Gives increased load capacity without a bigger bore (duplex, triplex etc. mountings).**
- **Empirical formulas exist for calculating life based on the applied loads and operating condition.**
- **A radial load on a tapered roller bearing induces a thrust load and vise versa.**
  - **One must take this into account when calculating equivalent radial loads.**

Allowance for thermal growth

- **Use same philosophy as for angular contact bearings.**
- **Timken™ provides the following method for finding the heat generated in their tapered roller bearings:**

1) Find the equivalent axial load using the bearing's load factor K and axial load factor f_t.

- **If $KF_{axial}/F_{radial} > 2.5$ then $F_{eq\ axial} = F_a$. Else $F_{eq\ axial} = f_t F_r / K$.**

2) Heat (Watts) is a function of the equivalent axial load, heat factor G (from mfg.), viscosity μ (cP) and speed S (rpm):

$$Q = 2.7 \times 10^{-7}\, G_1 S^{1.62}\, \mu^{0.62}\, F_{\text{axial equiv.}}^{0.30}$$

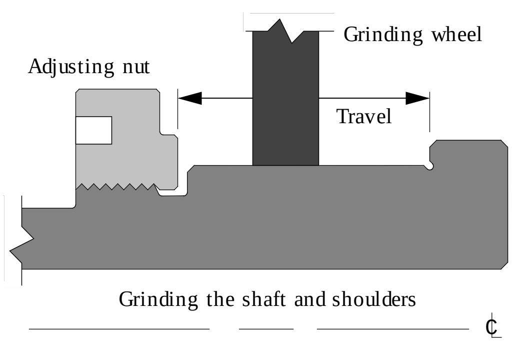
- **The viscosity of the oil depends on the oil temperature and hence flow rate of the oil.**
- **The flow rate (liters/min) required to remove all of the heat generated by the bearing is:**

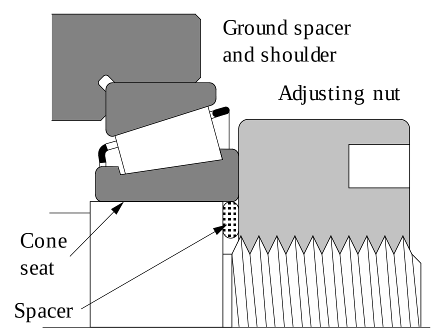
$$F = \frac{9.6 \times 10^{-9}\, G_1 S^{1.62}\, \mu^{0.62}\, F_{\text{axial equiv.}}^{0.30}}{T_{\text{oil out}} - T_{\text{oil in}}}$$

- **To accommodate various operating conditions, the flow rate should be chosen for the worst case.**
  - **A closed loop control system used to measure the oil temperature and adjust the flow rate.**

Alignment:

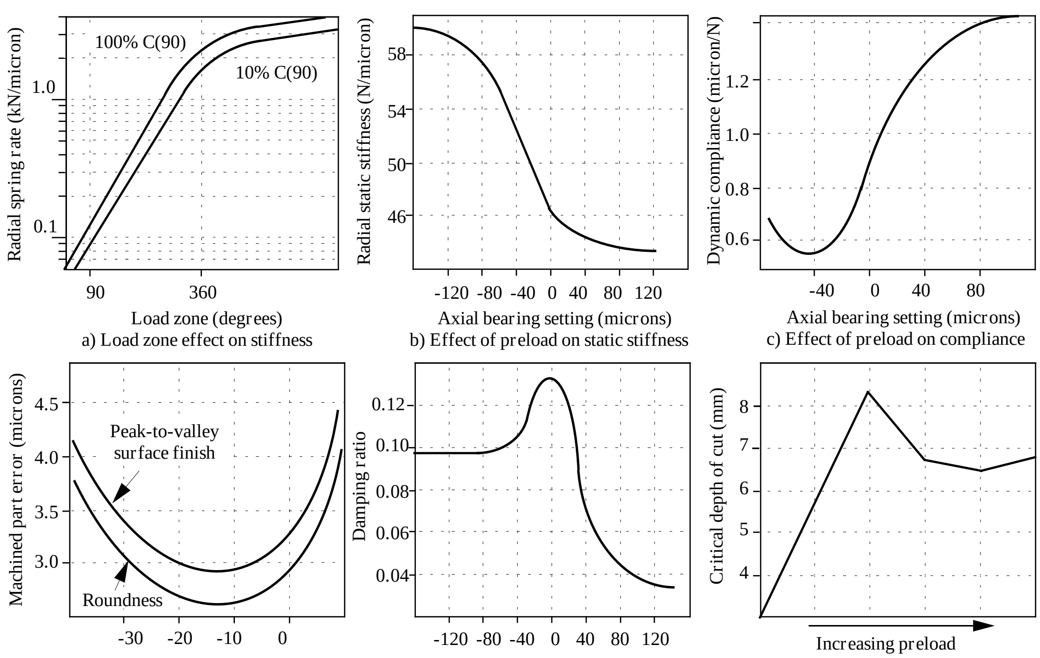
- **A single tapered roller bearing can tolerate a misalignment of about ±2' (0.582 mm/m).**
- **Misalignments of less than 0.001 radian (1 mm/m) generally do not affect the bearing's life.**
- **A duplex pair resists moment loads:**
  - **Has an alignment tolerance of essentially 0º with another pair used to support a long shaft.**
- **When using sets of tapered roller bearings at each end of a shaft (e.g. spindle):**
  - **The bore centerlines must be coincident.**
  - **The surfaces the races mate with at each end of the shaft are concentric.**
  - **The surfaces the cup and cone seat against be square with respect to the bearing centerline.**
- **Methods for improving seating surface squareness** (Courtesy of The Timken Co.)**:**





Preload adjustment:

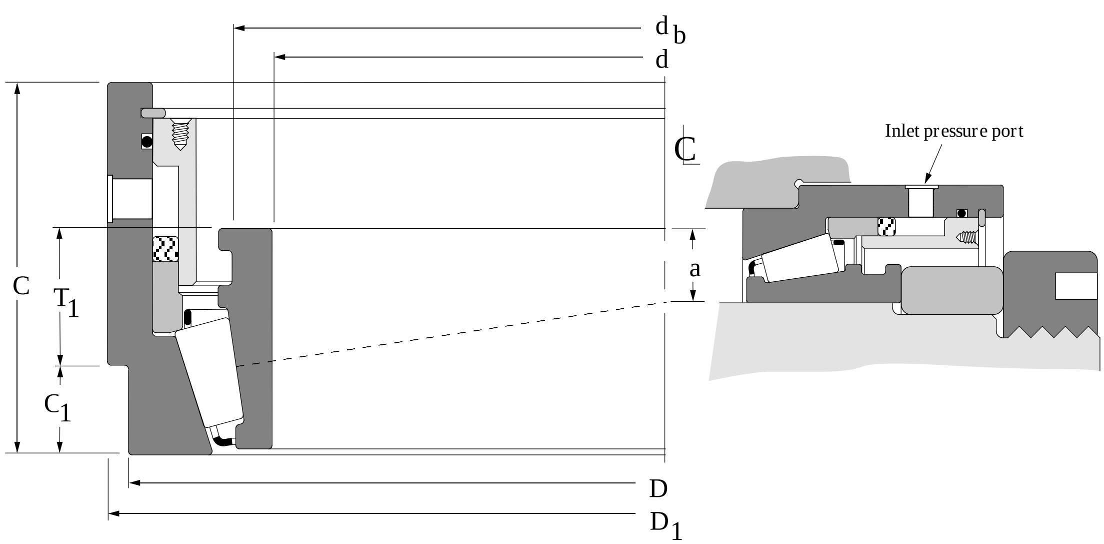
- **It is difficult to grind an offset in the races or make a spacer to geometrically set the preload.**
- **When economy is of prime importance:**
  - **The preload is often set using bolts that are tightened until the proper torque is reached.**
- **Also, the Poisson effect is more significant for tapered roller bearings.**
  - **When spacers are used to control the preload:**
    - **Extreme care must be taken and the manufacturer's guidelines strictly followed.**
- **Effects of tapered roller bearing preload on system performance** (Courtesy of The Timken Co.)**:**



a) Load zone effect on stiffness
b) Effect of preload on static stiffness
c) Effect of preload on compliance
d) Effect of preload on part error and surface finish
e) Effect of preload on damping
f) Effect of preload on metal removal rate

Hydra-Rib™ bearings

- **Thermal growth and applied loads can change the preload on bearings which in turn changes performance.**
- **To help maintain constant preload:**
    - **One could use a large spring to seat the cup or cone.**
    - **But then stiffness would decrease.**
- **An alternative is to force the tapered rollers further into the space between the cup and cone.**
- **Characteristics of Timken's Hydra-Rib™ bearing** (Courtesy of The Timken Co.)**:**

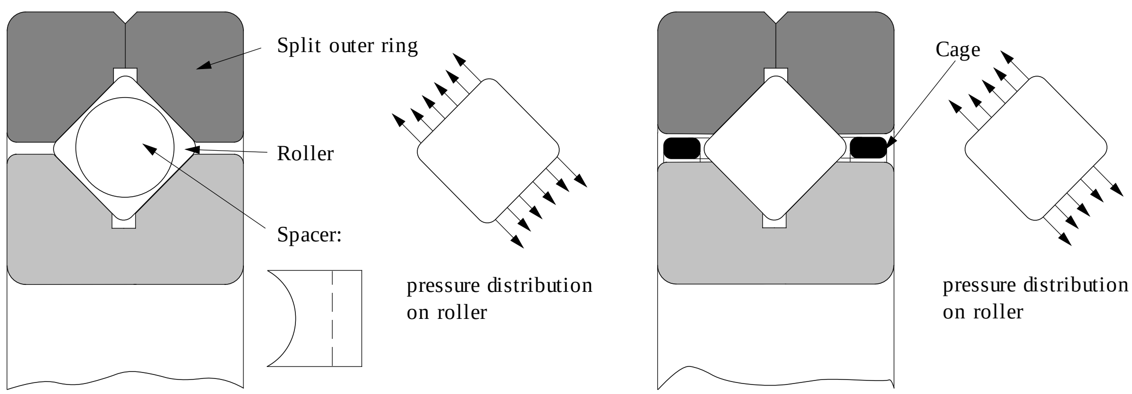


Spherical roller bearings

- **Roller bearing equivalent of self aligning ball bearings.**
- **The spherical rollers rest in a spherical race and allow for shaft misalignment on the order of 2^{o}.**
- **Single row spherical roller bearings have very high radial load capacity but low axial load capacity.**
- **Double row spherical roller bearings, with inclined roller axes, have high radial and thrust capacity.**
- **Used mainly in large industrial machinery:**
  - **Where it is difficult to align large bores with the precision required by tapered roller bearings.**
- **Typically preloaded by axially displacing the inner ring with a tapered inside diameter over a tapered shaft.**
- **For reversing thrust loads, use an oppositely configured bearing or an opposed axial restraint for the inner ring.**
- **The thrust load must not pull the bearing further onto the tapered shaft which would overload the bearing.**

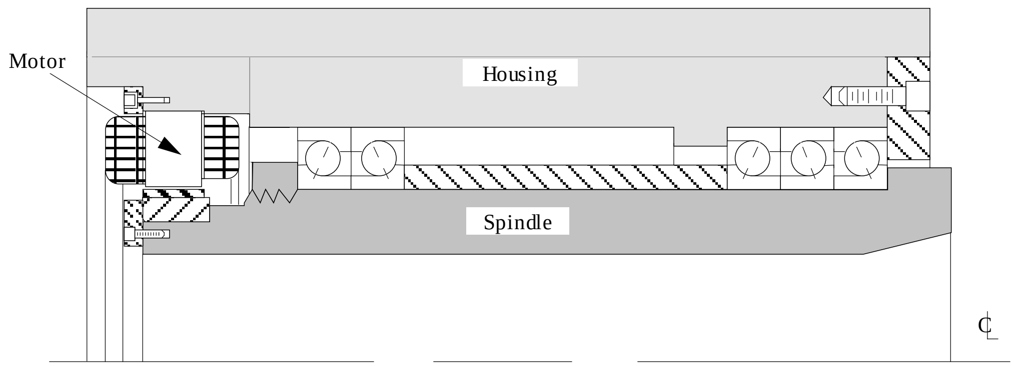
Crossed roller bearings

- **A thin section bearing that uses rollers to maximize load capacity and stiffness.**
- **Often used on low profile precision rotary index tables.**
- **Comparison of cross roller bearings with spacers and cages** (Courtesy of THK Corp.)**:**

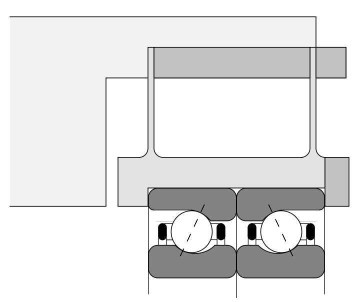


Thermocentric design

- **The orientation of the bearing contact forces can be chosen to maintain preload in the presence of changing temperature.**
- **Back-to-back angular contact bearing spindle design with rear bearing's outer ring sliding in housing bore:**



- **Letting one set of bearings float has the following design problems:**
  - **More bearings are needed.**
  - **Tighter alignment tolerances between the front and rear bores are needed.**
  - **Expansion of the rear bearings' outer rings could prevent them from being allowed to float in the rear bore.**
    - **Consider using a diaphragm flexure based mount for the rear bearings:**



- **If the bearings are to be mounted so the front bearings preload the rear bearings:**
    - **The spacing of the bearings in relation to their size is critical.**
        - **Preload must remain constant in the presence of changing temperature.**
        - **This is often best done with the use of a spring-type preload.**
    - **The proper spacing is a function of several parameters that are very difficult to quantify.**
- **This is called *thermocentric* design.**
- **To the first order, tapered roller bearings' design is thermocentric when:**
    - **The projections of both bearings' rollers' axes meet at a common point on the shaft centerline.**
- **For angular contact bearings:**
    - **The lines (through the balls) orthogonal to the contact vectors should meet on the shaft centerline.**