FUNdaMENTALS of Design

Topic 10
Bearings

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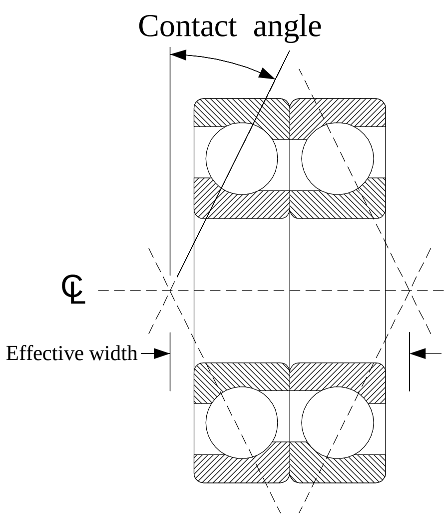
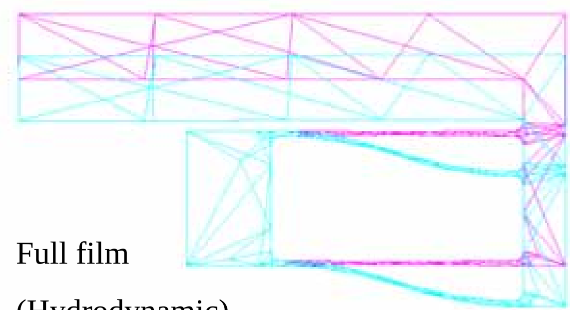
Topic 10
Bearings

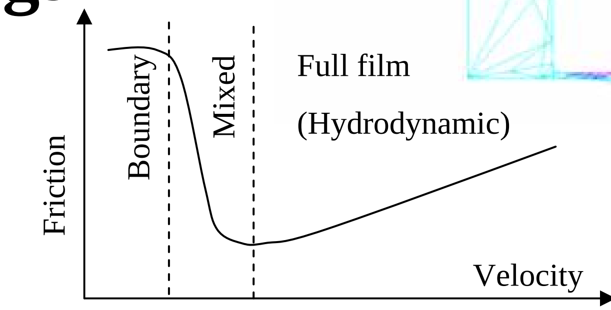


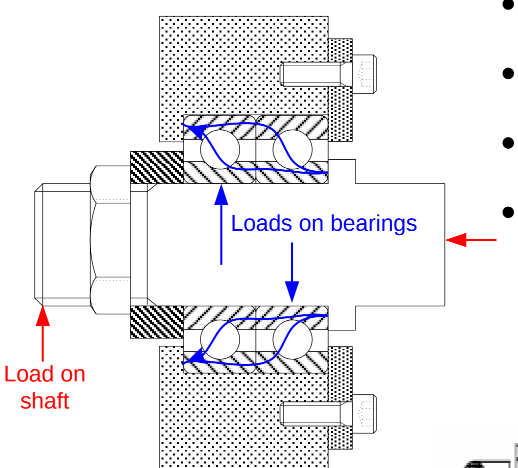
Back-to-back bearing mounting

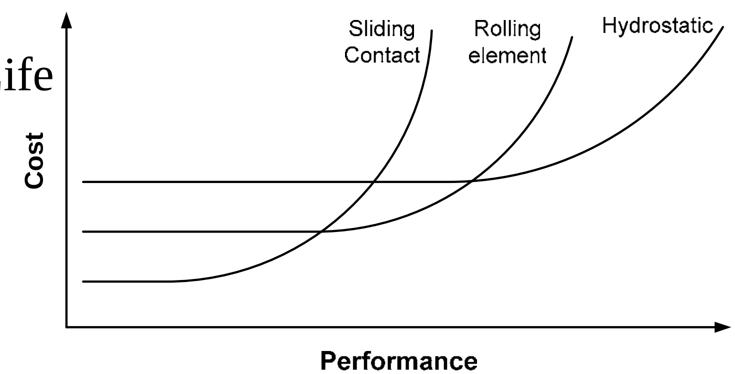
Topics

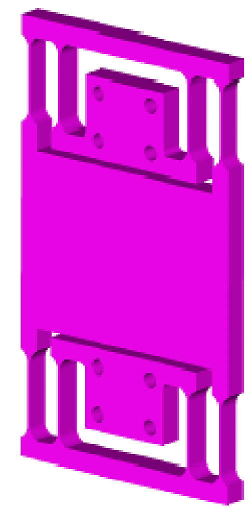
- In the Beginning…
- Contact Bearings
- Non-Contact Bearings
- Preload
- Mounting
- Loads, Lube & Life
- Dynamic Seals
- Error Motions

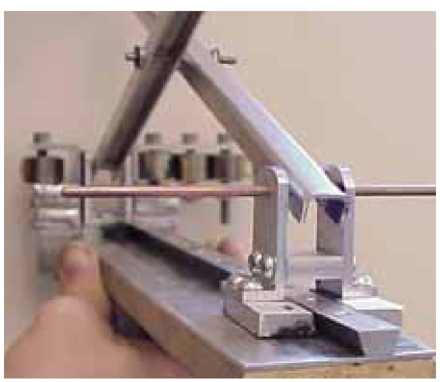


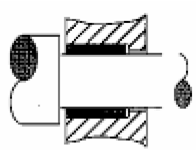




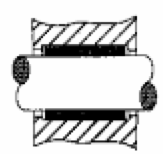




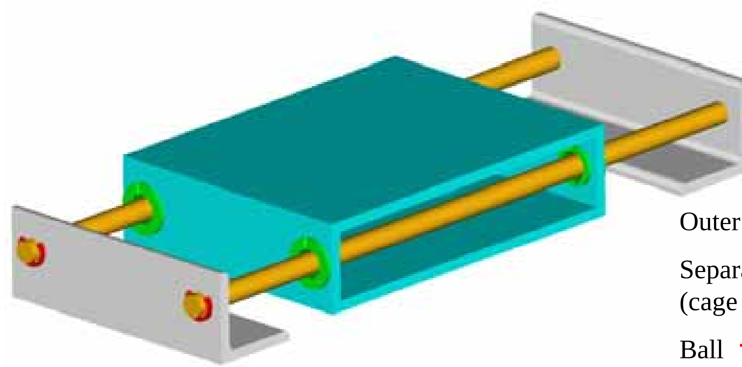


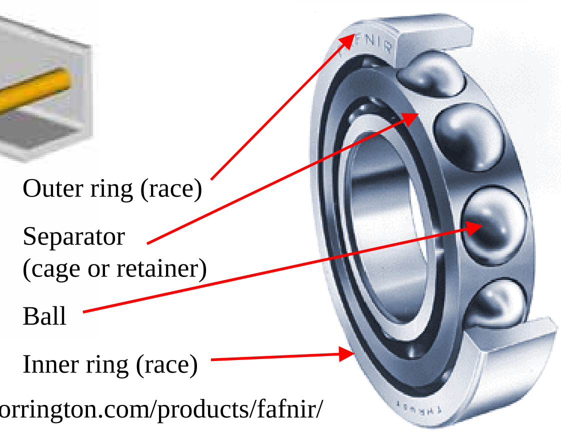


Shaft and housing shoulders



Housing undercut





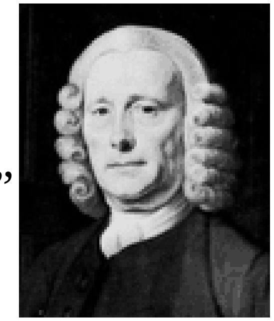
http://www.torrington.com/products/fafnir/

Henry Timken
1831-1909

Heinrich Hertz
1857-1894

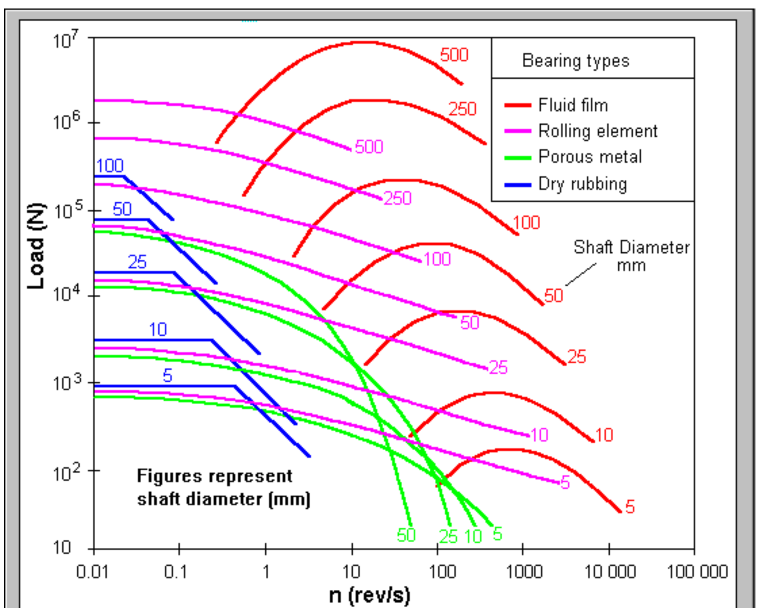
In the Beginning…

- *Bearing* is defined by Webster's to be "a support or supporting part"
  - In machines, a *bearing* is a component that allows for relative motion between two parts
    - Your skeleton is the central structure that supports your body
    - Your body's joints are bearings that allow different parts to move
- Bearings can have many forms, but only two types of motions
  - Linear motion or rotary motion
    - Mechanical contact bearings: *Sliding*, *Rolling*, *Flexing*
    - Non-contact bearings: *Fluid Film*, *Magnetic*
  - One must understand the flow of forces and mechanical constraints



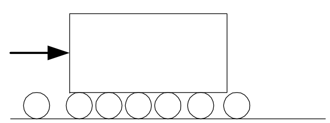
John Harrison
(1693–1776)

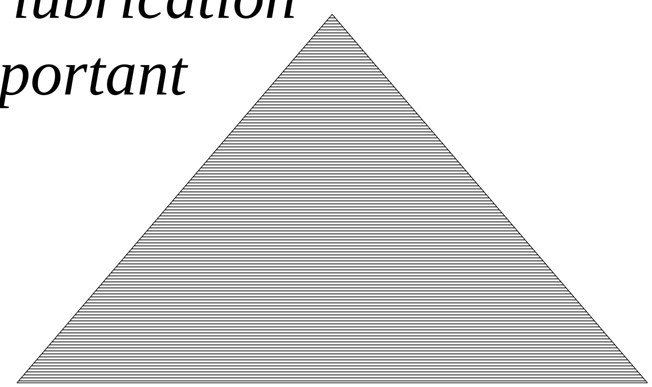
Leonardo da Vinci
1452–1519



Reproduced from the Tribology Handbook by M. J. Neale

Cleanliness and lubrication are most important





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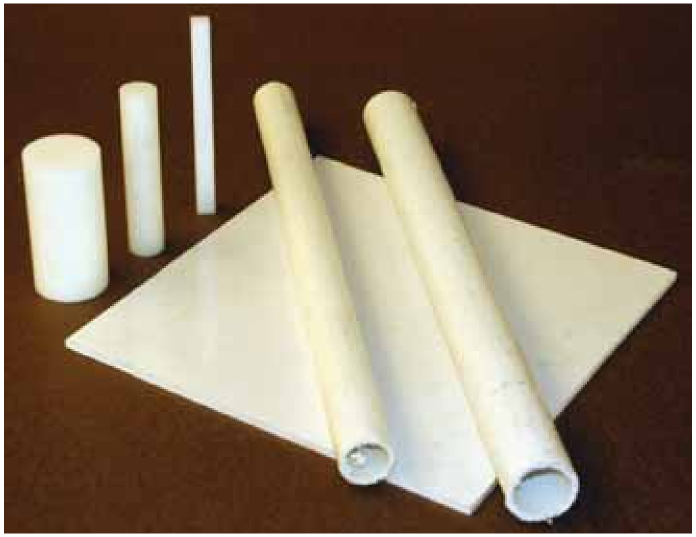
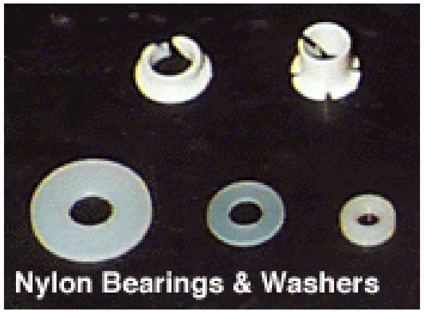
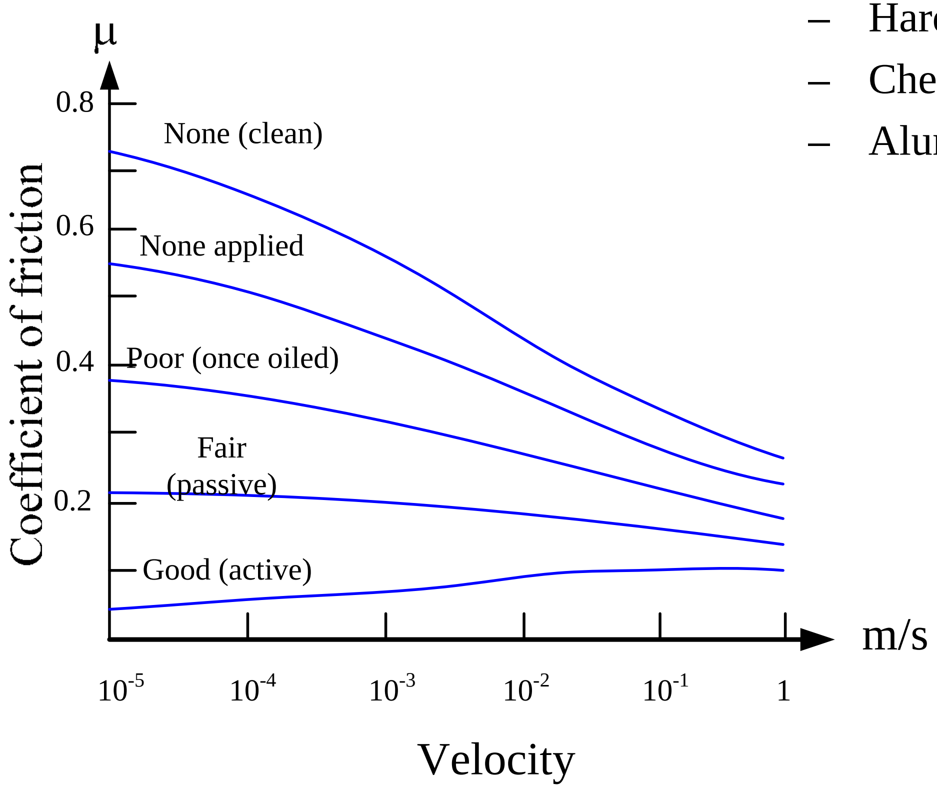
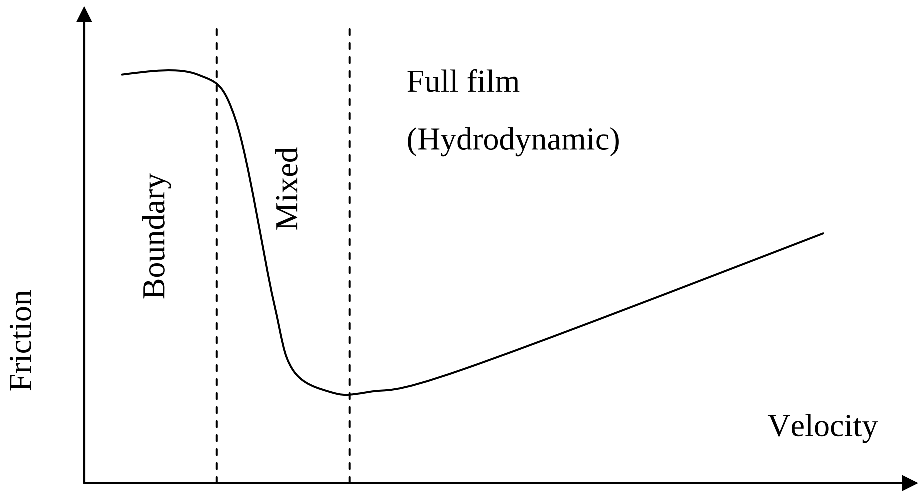


Contact Bearings: *Sliding Contact*



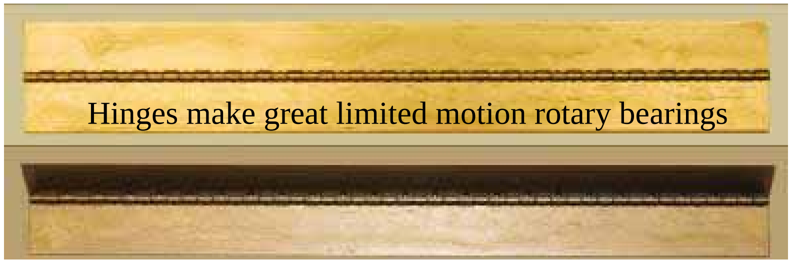
- Sliding contact bearings are commonly used for low speed applications
  - They rely on boundary lubrication to reduce wear and friction
- Polymers, brass, and ceramics are commonly used
  - Hard materials (shaft) slide on soft materials (bushing)
  - Check maximum static pressure and also the PV value
  - Aluminum-on-aluminum is to be avoided!



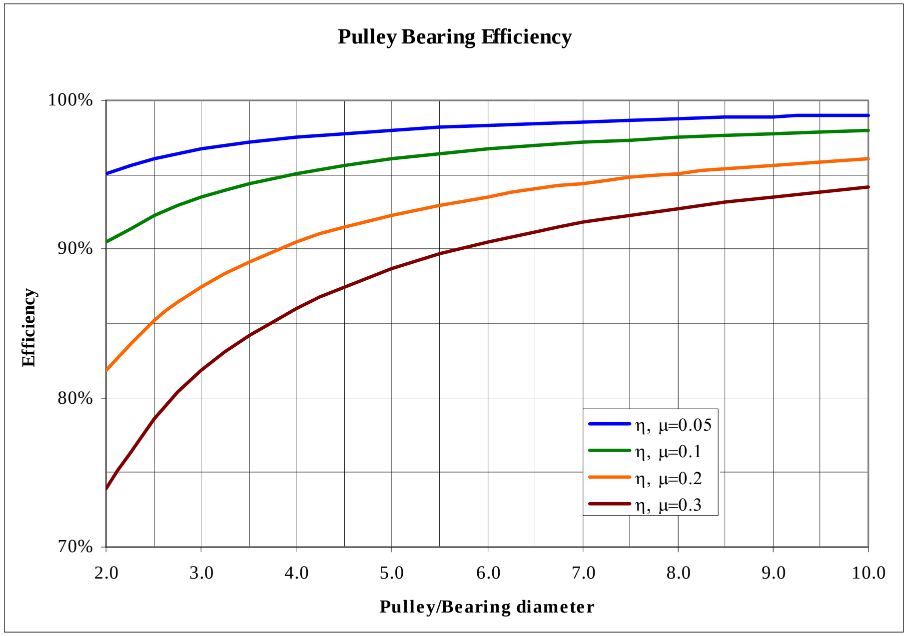


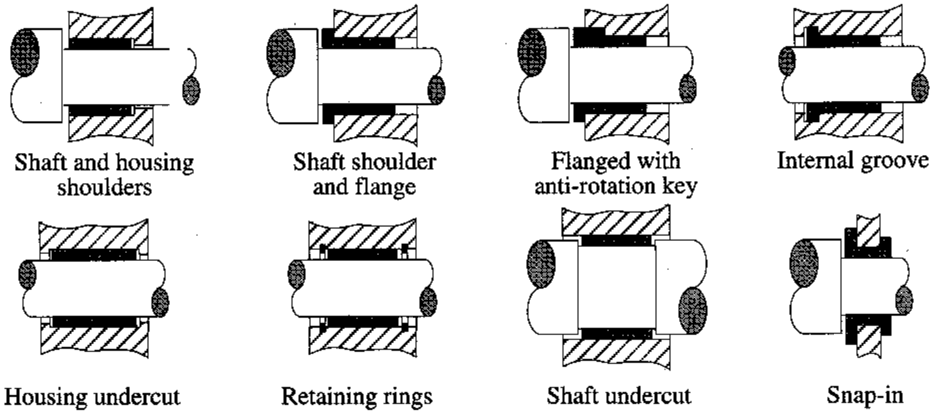
Stribeck curve

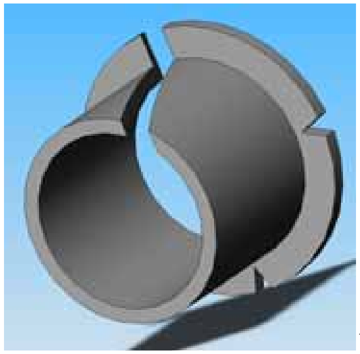
Sliding Contact: *Rotary Motion*

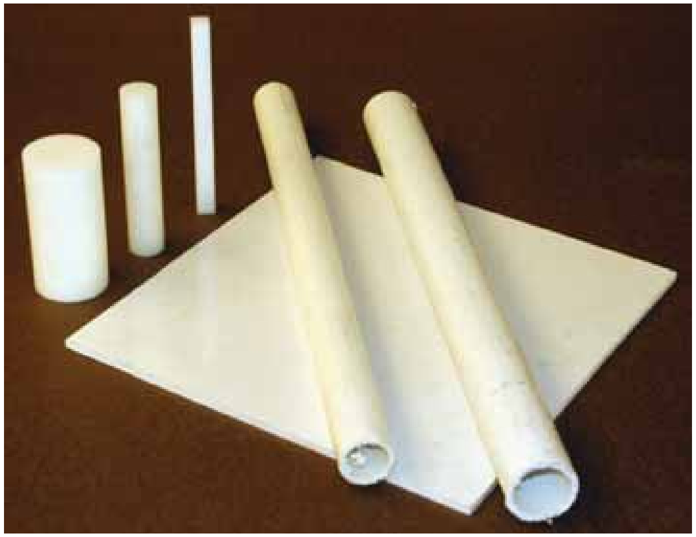


- Modular sliding contact bearings are found in many catalogs
  - Molded polymer and sintered bronze bearings can be impregnated with lubricants
    - Low-cost Nylon spacers ("standoffs") used in electronics work well for design contests
- Also used for linear motion on round shafts
- Flat washers can be used for thrust loads (thrust washers)







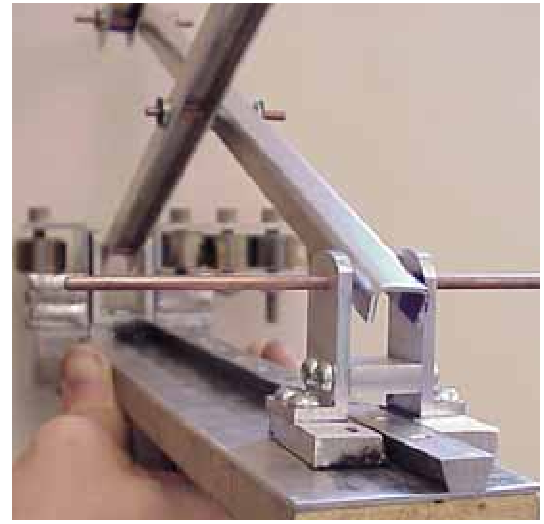


Can you imagine a split housing with a bolt to squeeze the bearing to set bearing-shaft clearance?

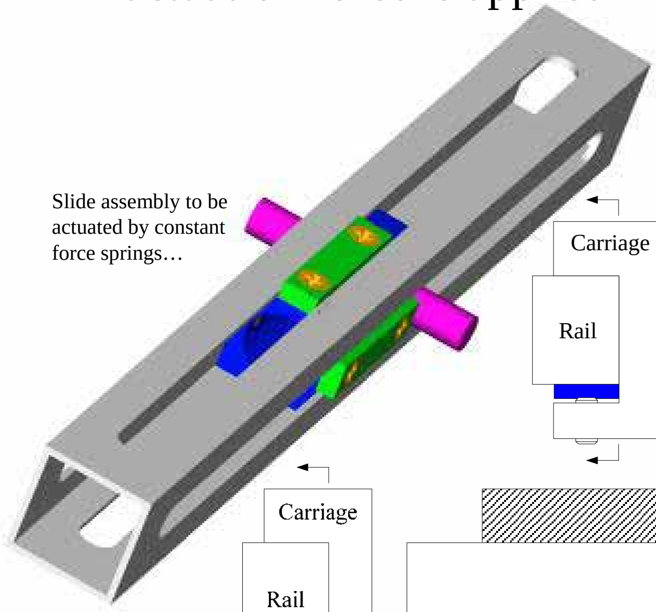
Pillow blocks from www.mcmaster.com

Sliding Contact: *Linear Motion*

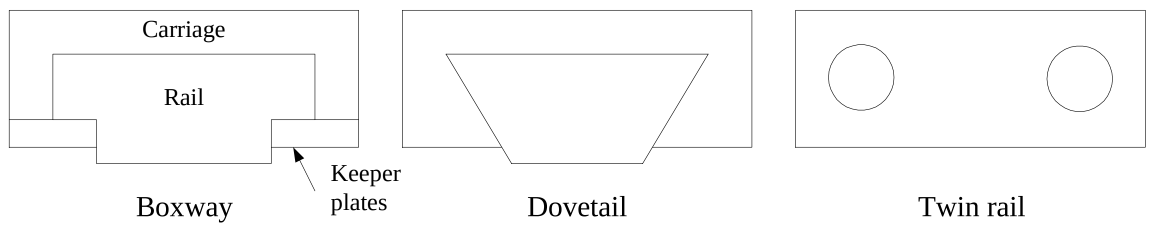
- Linear bearings are essentially rotary bearings with a really large radius of curvature
  - There are many configurations: boxways, dovetail, twin rails…
  - Clearance between bearing and rail or shaft can be removed by circumferential clamping or with *gibs*
- Apply *Saint-Venant's* principle to the ratio of the length of the carriage to the spacing of the bearings to prevent jamming
- Beware *centers of mass*, *stiffness*, *friction*, and where the actuation force is applied

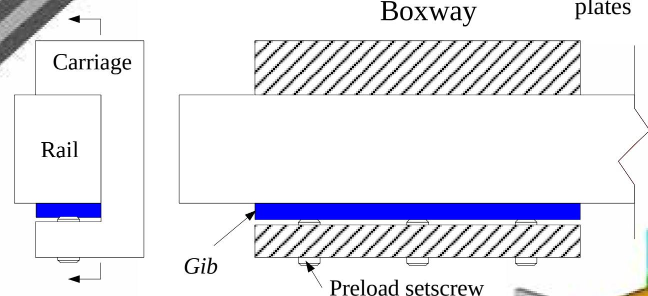


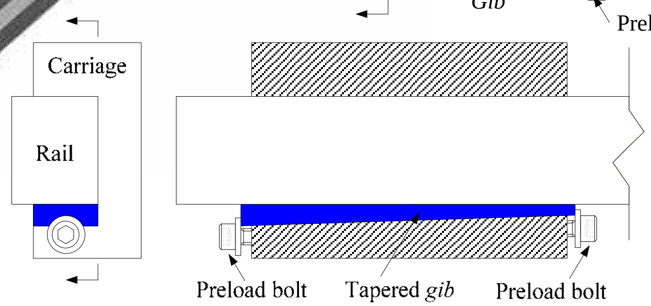
Bryan Ruddy used sliding contact dovetail bearings to guide his scissor linkage

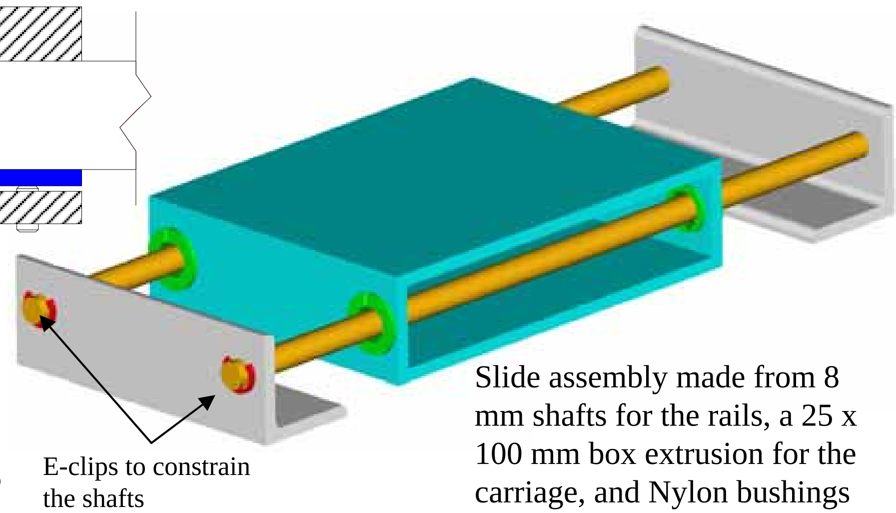


Slide assembly to be actuated by constant force springs…

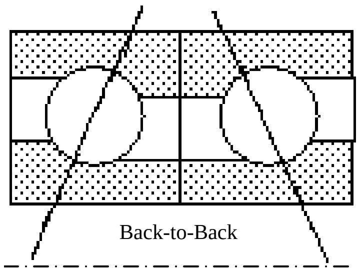




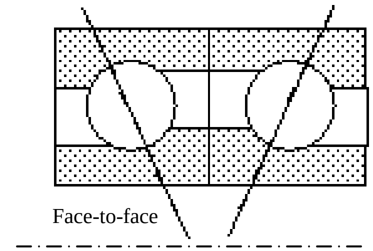


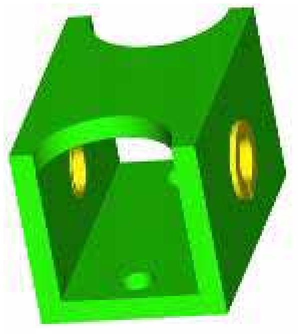


Slide assembly made from 8 mm shafts for the rails, a 25 x 100 mm box extrusion for the carriage, and Nylon bushings

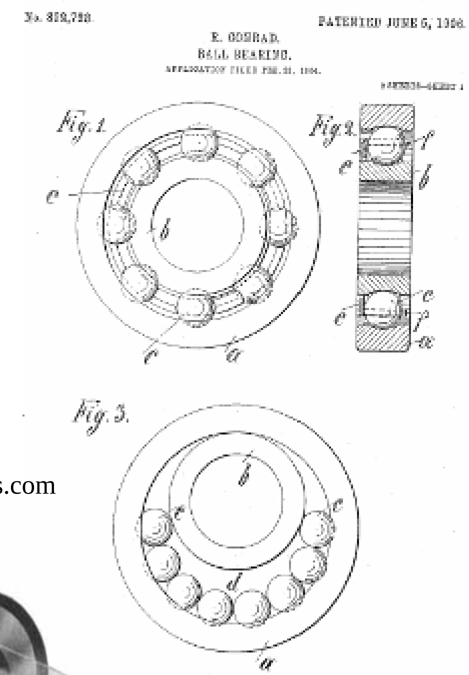


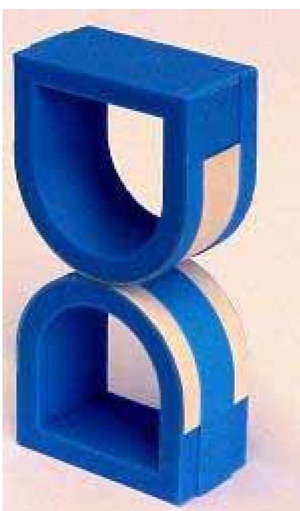
Contact Bearings:
Rolling Elements



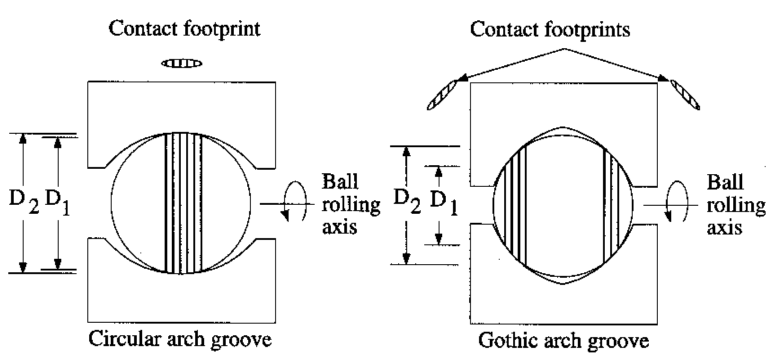


- Anti-friction bearings use rolling elements (balls or rollers) to reduce friction
- Linear and rotary bearings can use rolling elements
  - Axial, thrust, and moment loads can be supported depending on the bearing and how it is used in conjunction with other bearings
- Rotary bearings are naturally recirculating
  - Linear bearings can be non-recirculating (limited range of motion, extra low friction) or recirculating (unlimited range of motion)





Rolling joint model by Dr. Just Herder of the Delft University of Technology



2 points of contact

2 points of contact

http://www.thomsonindustries.com

Note difference in differential slip caused by rolling on different diameters. Can this be a + effect?

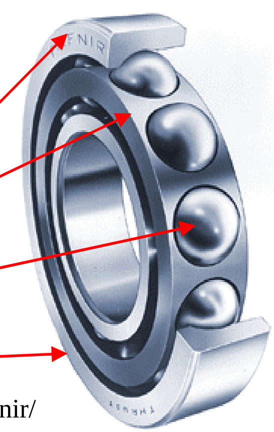
$$\%_{slip} = \frac{D_2 - D_1}{D_2} \times 100$$

Outer ring (race)

Separator (cage or retainer)

Ball

Inner ring (race)



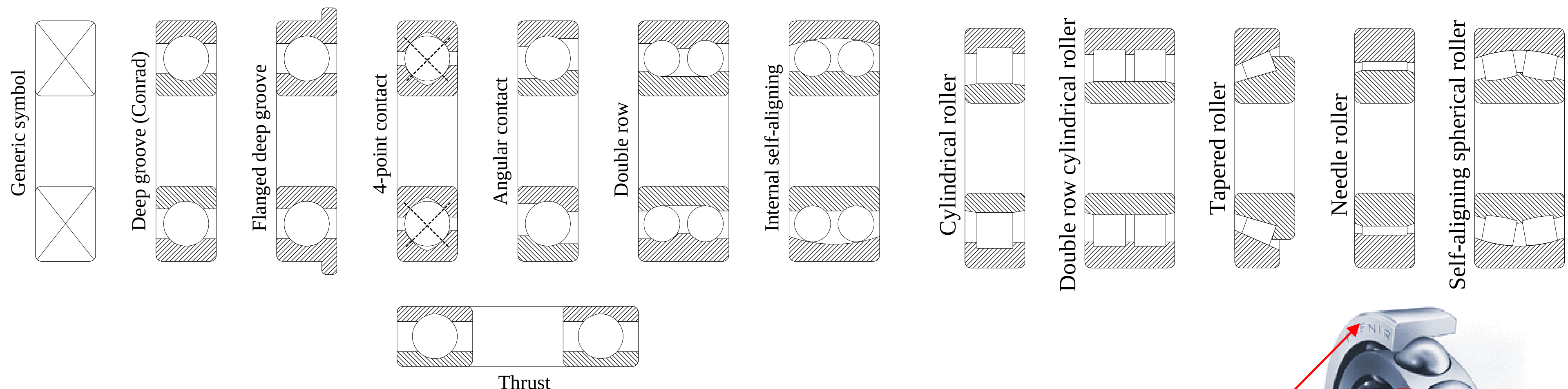
http://www.torrington.com/products/fafnir/

Rolling Elements: *Rotary Motion*

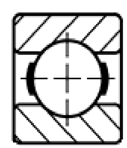
http://www.timken.com

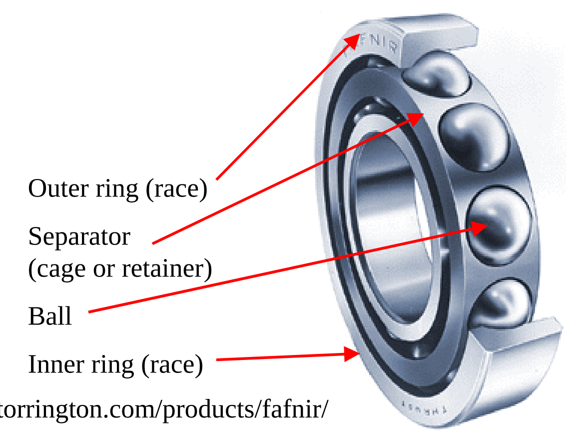
- Bearing speed is limited by its DN value, where D is the diameter in mm and N is the allowable rpm
  - Shear power is the product of velocity ($R\omega$) and force ($R\omega\mu A/h$) and thus is equal to $(R\omega)^2\mu A/h$
  - Centrifugal load is proportional to $r\omega^2$
- *Scrutinize mountings and beware over constraint!*

http://www.torrington.com/products/fafnir/



Bearing	Cage	ABEC-1		ABEC-1		ABEC-1		
		Grease	Oil	Grease	Oil	Grease	Oil	Oil Mist
Radial and angular contact, single row (rpm)	Molded nylon	300,000	350,000	300,000	400,000	400,000	600,000	750,000
	Composite	300,000	350,000	300,000	400,000	400,000	600,000	750,000
	Metallic	250,000	300,000	-	-	-	-	-





http://www.torrington.com/products/fafnir/

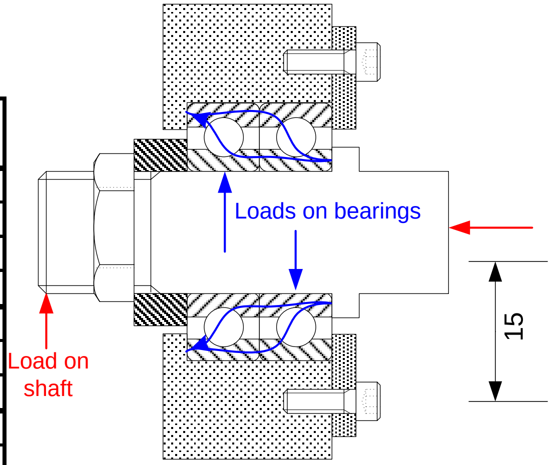
Rotary Motion: *“Ball Bearings”*

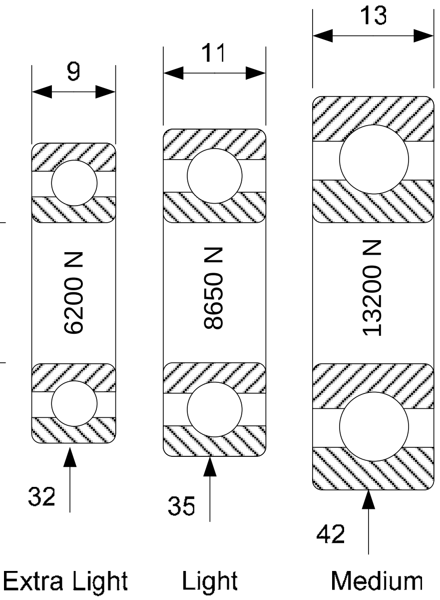
Leonardo da Vinci
1452–1519

- Deep groove, “Conrad”, ball bearings are the most common form of ball bearings
  - Radial loads, & bidirectional axial loads equal to the radial load because all balls share the load
    - Balls have to roll from one side of the contact groove to the other, so bidirectional stiffness is non-linear
    - Same bore-size, different duty bearings have different outer dimensions and load capacities
- Angular contact bearings’ contact grooves are preferentially ground on one side, and can accurately support both radial and uni-directional axial loads
  - The most accurate of ball bearings, often used for high speed applications
- Deep Groove and Angular Contact ball bearings are used in pairs to support moment loads
- Four-point contact ball bearings have gothic arch grooves that allow each ball to contact two points of each raceway, and thus allow a single bearing to support radial, axial, and moment loads
  - Giant forms of these bearings, with gear teeth on the inner or outer race, are called slewing rings and they are used as turntable bearings for cranes, excavators…

	ID (mm)	OD (mm)	Width (mm)	Cstatic (N)	Cdynamic (N)
Extra Light 9100	10	26	8	1960	5100
	15	32	9	2500	6200
	280	420	65	430000	360000
	600	870	118	1539000	800000
Light 200K	10	30	9	2650	6550
	15	35	11	3450	8650
	280	500	80	710000	560000
Light 200W (full compliment)	15	35	11	5000	11000
	280	500	80	1120000	765000
Medium 300K	10	35	11	3750	9000
	15	42	13	5600	13200
	280	580	108	780000	585000

Data from The Torrington Company Service Catalog, 1988

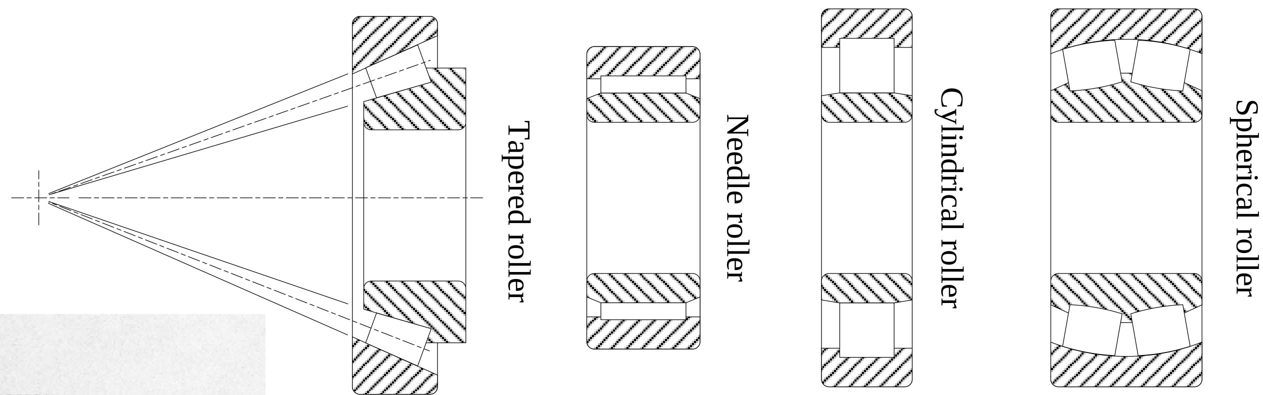


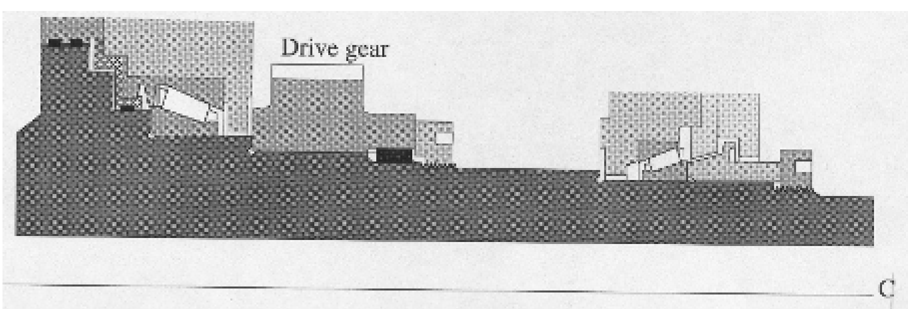


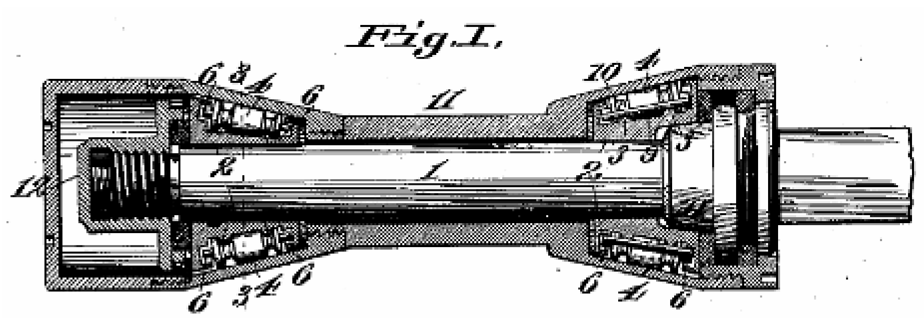
Rotary Motion: *“Roller Bearings”*

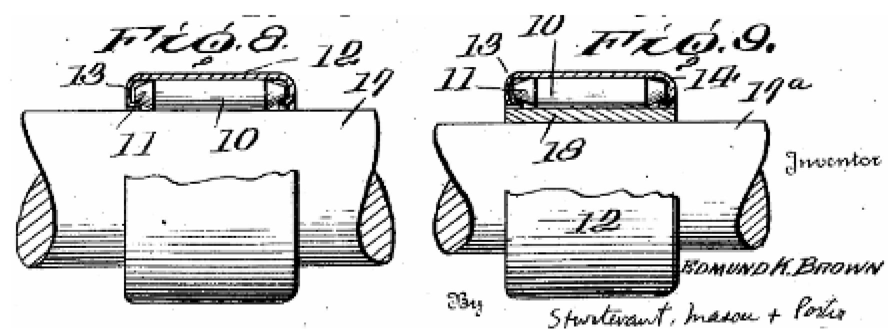
- Line contact gives roller bearings many times the load capacity of a similarly sized ball bearing
- Tapered roller bearings are the roller equivalent of angular contact ball bearings
  - Invented by Henry Timken in 1898, it revolutionized modern industry by simplifying the design of heavy machinery such as railroad axle bearing supports.
- Spherical roller bearings revolutionized steel and paper making by allowing huge rollers to be supported on rolling element bearings without structural deformations overloading bearings

See harrison museum email…





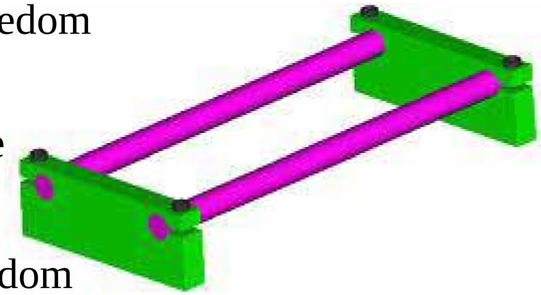


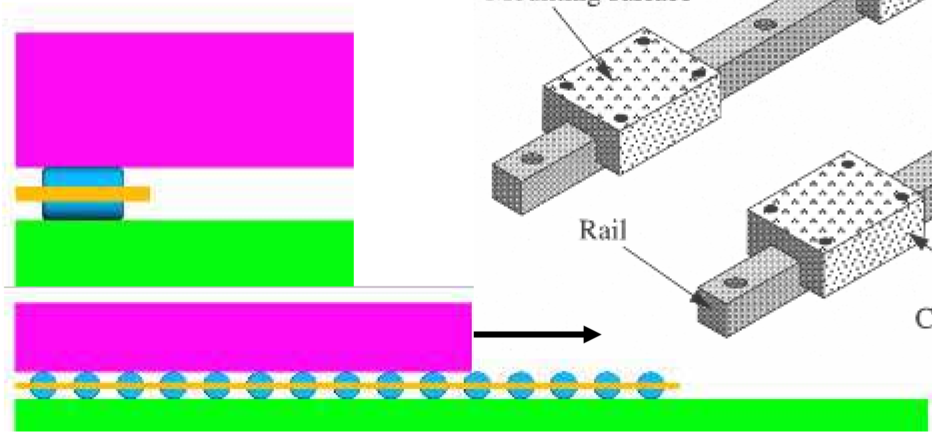


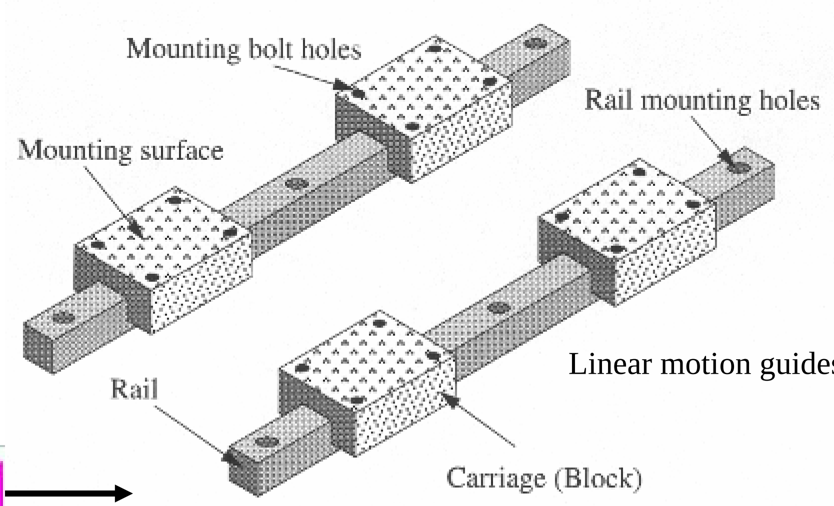
Rolling Elements: *Linear Motion*

BallBushing™ from www.thomsonindustries.com

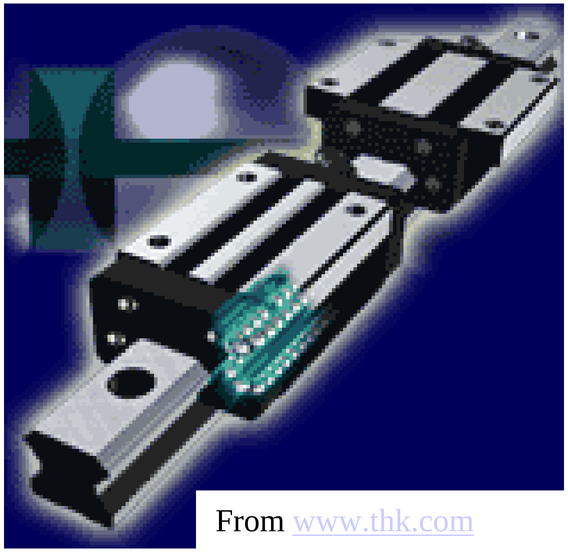
- Linear rolling element bearings can be non-recirculating or recirculating
- Non-recirculating types: wheels (cam followers) & rolling elements
  - More complex arrangements are needed to constrain 5 degrees of freedom
  - Wheels on rails can roll very far
  - Rollers between two surfaces travel half-as-far as the moving surface
- Recirculating types: *linear guides* & *ball bearing bushings*
  - Modular form makes then easier to use to constrain 5 degrees of freedom
  - Travel distance is only limited by ability to splice together rails
- *Scrutinize mountings and beware overconstraint!*







Linear motion guides

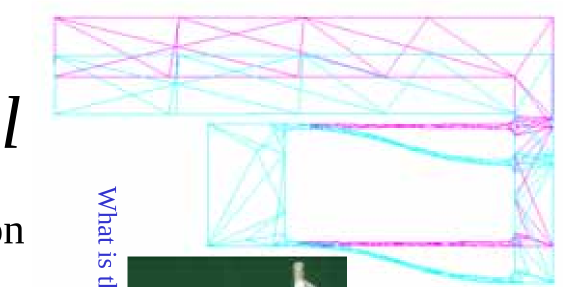


From www.thk.com

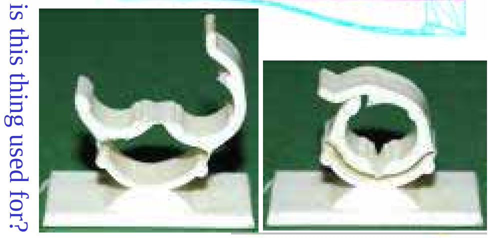
Section through a flexural pivot

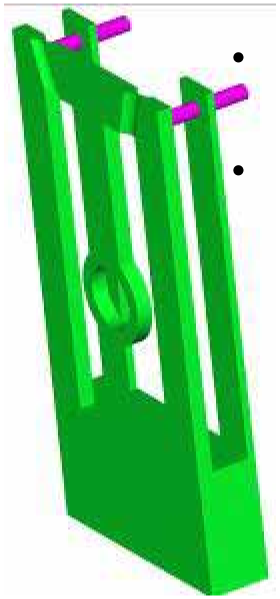
Contact Bearings: *Flexural*

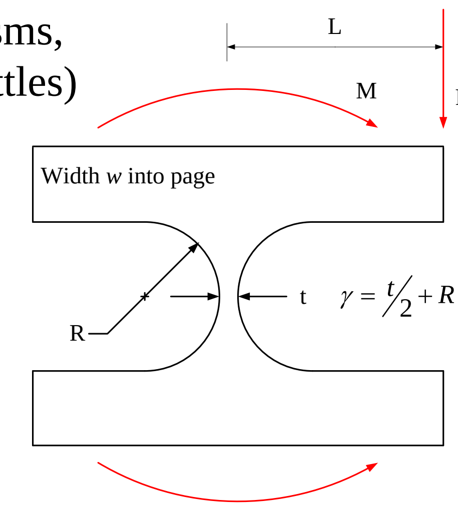
- Flexures use elastic deformation to provide the desired motion
- Linear and rotary motion flexures can be created
  - The challenge is to manage stress and constraints
- In general, for machines, a long-life flexure will be 20x larger than the range of motion that it can provide
- Wide range of applications from precision mechanisms, (wafer steppers), to consumer products, (flip-top bottles)

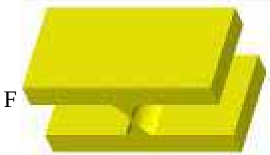


What is this thing used for?





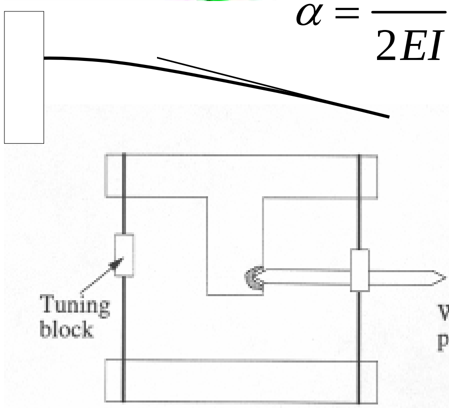




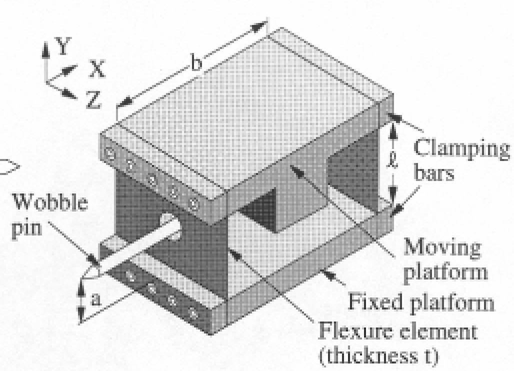
$$\delta = \frac{F L^3}{3EI}$$

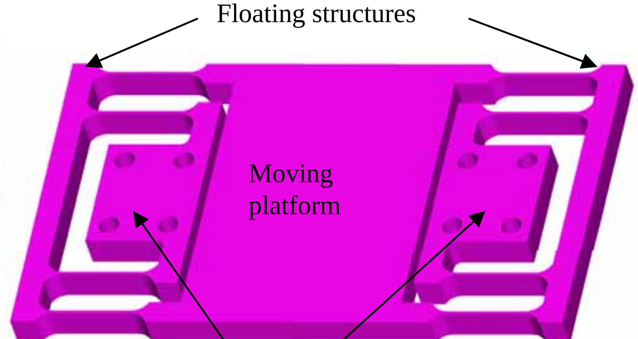
$$\alpha = \frac{F L^2}{2EI}$$

Its either the wonderfully designed top and flip-top cover (with flexural hinge), OR a happy space alien couple!



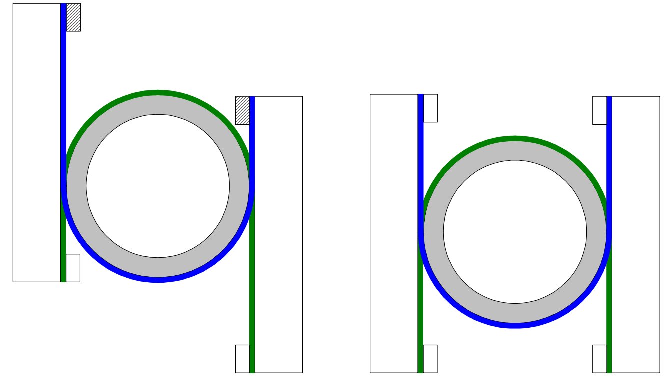
Four-bar linkage flexure



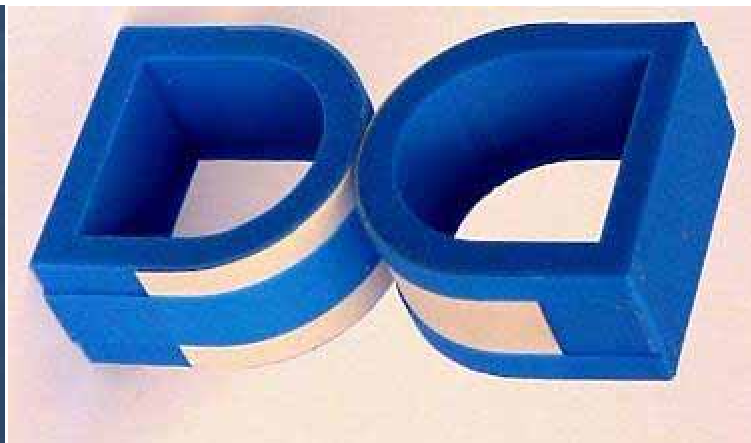


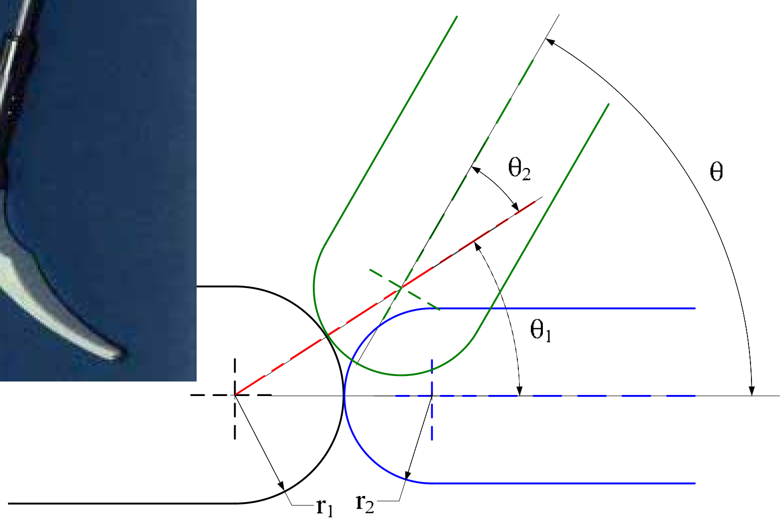
Contact Bearings: *Flexural Rolling*

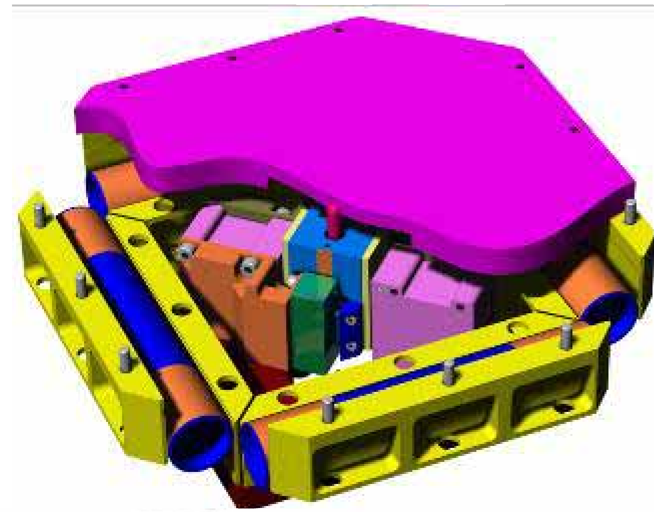
- The hybrid combination of flexing & rolling can provide the best of both worlds
  - Large rolling surfaces can provide accurate motion
  - Thin flexible bands constrain the rolling surfaces



Rolling joint model and forceps images provided by Dr. Just Herder of the Delft University of Technology







Patent pending

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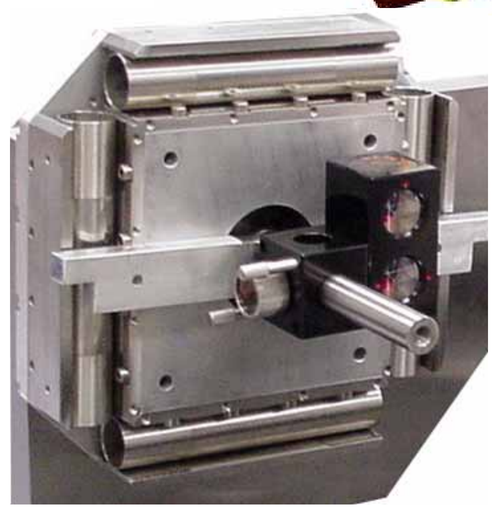
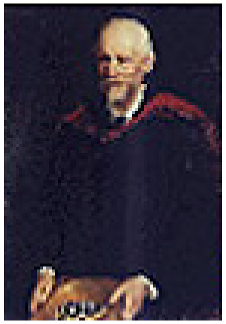
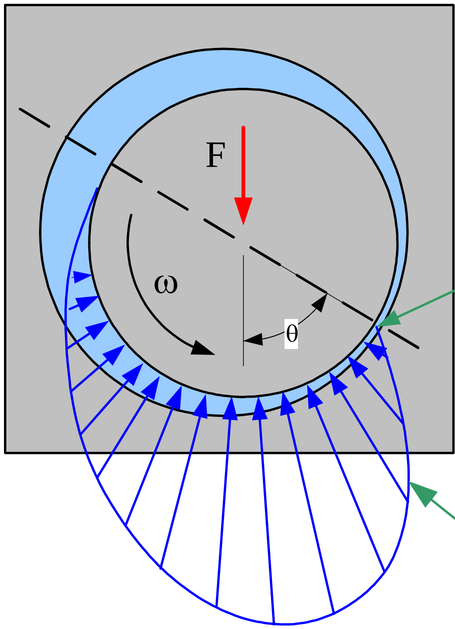


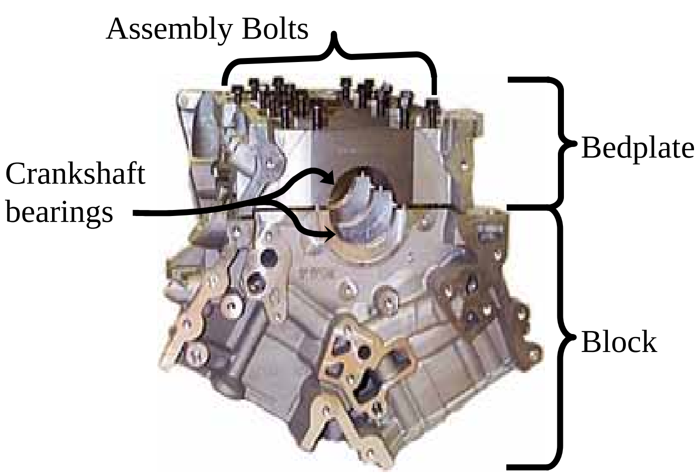
Non-Contact Bearings: *Hydrodynamic*

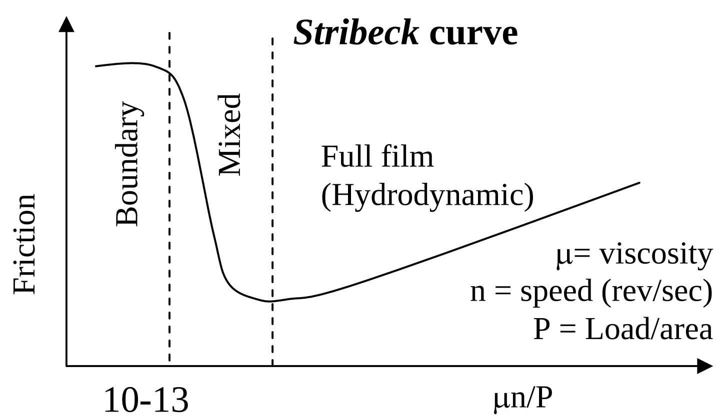


Osborne Reynolds (1842 - 1912)



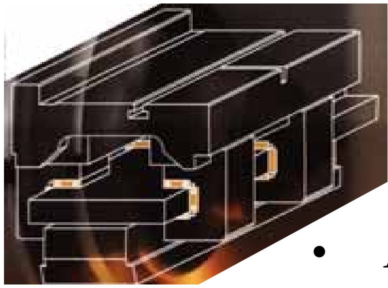
- The industrial revolution was made possible by rotating shafts that were supported by a thin film of lubricant induced by *hydrodynamic* shear
  - Velocities must typically be greater than 0.1 m/s
    - Strongly dependant on lubricant viscosity
  - As long as a shaft is rotating with sufficient speed, and lubricant is available, hydrodynamic bearings can provide good load capacity and long life in a small space
  - Their simplicity and low cost makes them widely applicable
- They have several drawbacks compared to anti-friction (rolling element) bearings
  - They consume more energy
  - They are less accurate
    - The axis of rotation position varies with load & speed
  - However, they can last "forever" if they are never stopped





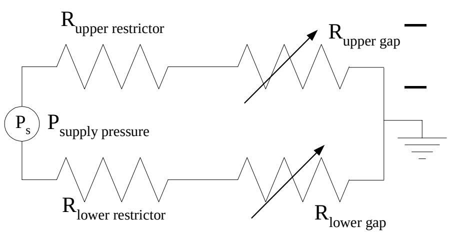
Albert Kingsbury 1863-1943

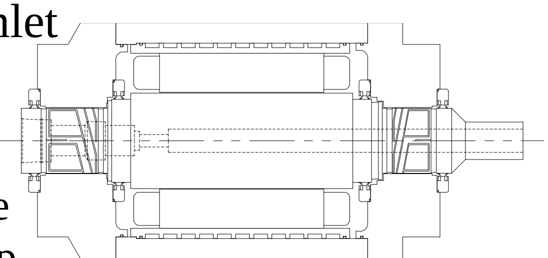
Non-Contact Bearings:
Aerostatic & Hydrostatic



Weldon's 1632 Gold grinding machine carriage

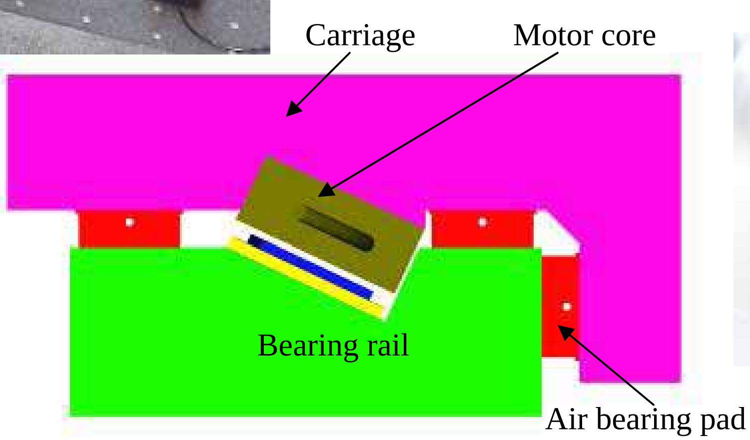
- Aerostatic & hydrostatic bearings rely on an external pressure source to supply gas or liquid through an inlet restrictor to a bearing pad
  - The bearing pad has resistance to flow to atmosphere
  - This forms a resistance network where pressure in the bearing is a function (nonlinear, gap cubed) of the gap between the bearing and the rail on which it runs
- Gas bearings do not require collection systems
  - Pressures are typically limited to 6 atm
- Liquid bearings typically use collection systems unless cutting fluid (e.g., water for ceramics) can be used
  - Pressures are typically 40 atm, but can be 200 atm



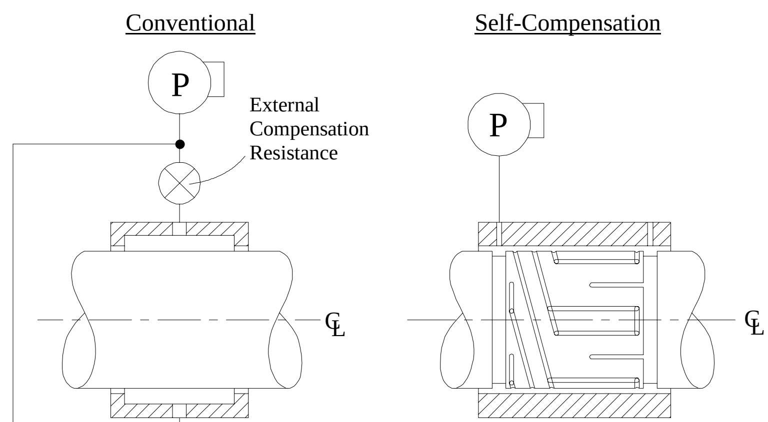


Dr. Kevin Wasson & David Gessel, Aesop, Inc.

US Patent 5,700,092



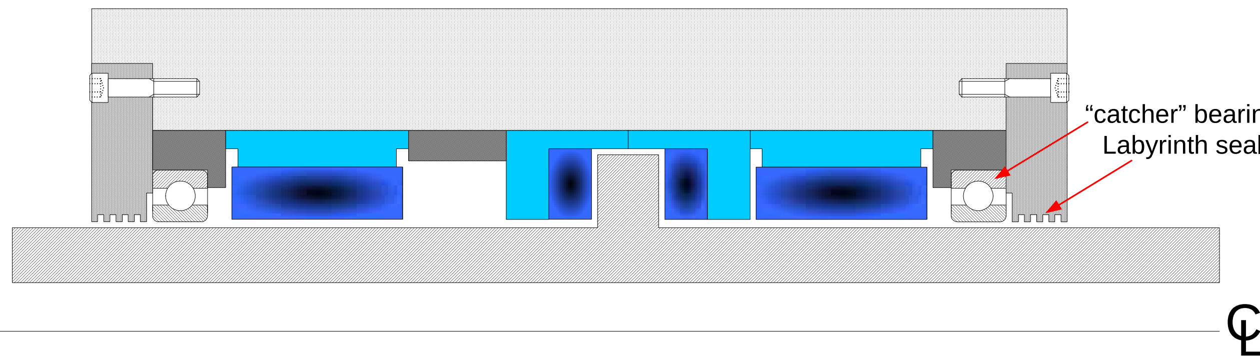
US Patents 5,488,771 & 6,150,740



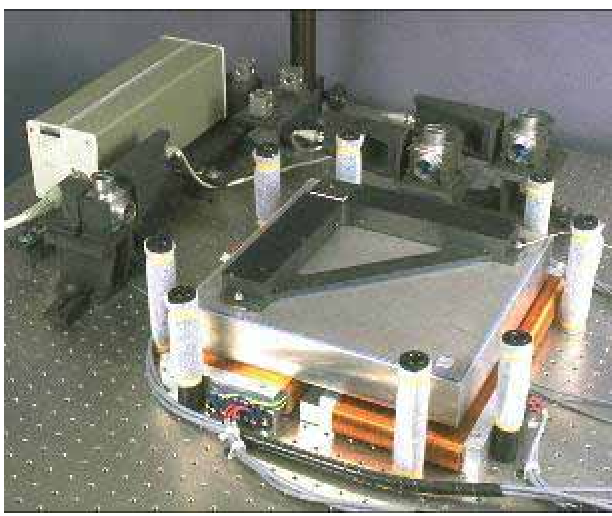
See Dr. Kevin Wasson's Ph.D. thesis: "High Speed Hydrostatic Spindle Design" MIT, Mech. Eng 1994.

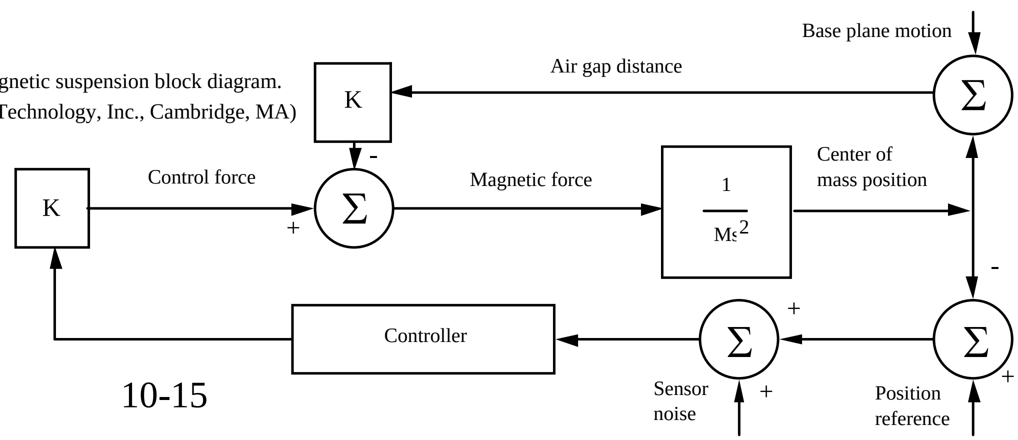
Non-Contact Bearings: *Magnetic*

- Magnetic bearings have NO mechanical contact with the supported component
  - No speed limits: heat is only generated by shearing of the air between the coils and component
- Linear, rotary, or combined motions can be supported
  - Mechanical *catcher* bearings are also often used in case the power fails
- Sophisticated position feedback measurement and control systems are required
- First-order estimates of load capacity can be made by assuming a maximum "bearing pressure" (see page 7-10) on the order of 0.5 atm.



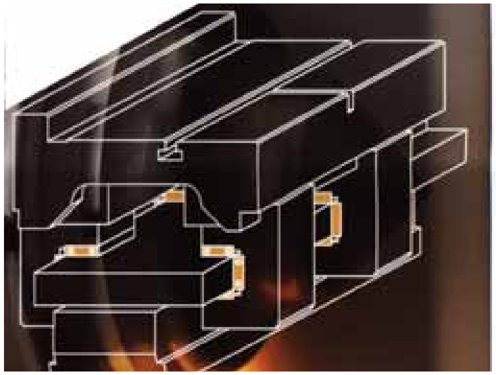
Magnetic bearing levitated stage from Prof. David Trumper's lab: http://web.mit.edu/pmc/www/Projects/Planar/planar.html



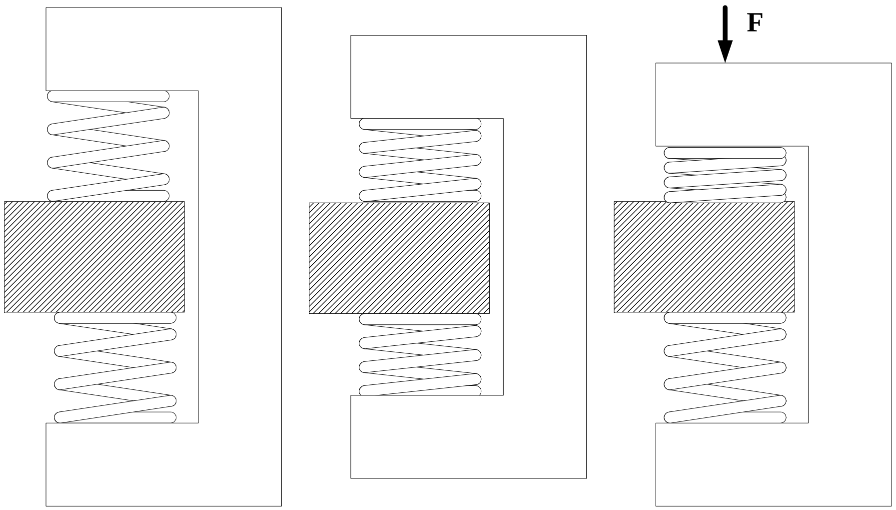


Basic magnetic suspension block diagram. (SatCon Technology, Inc., Cambridge, MA)

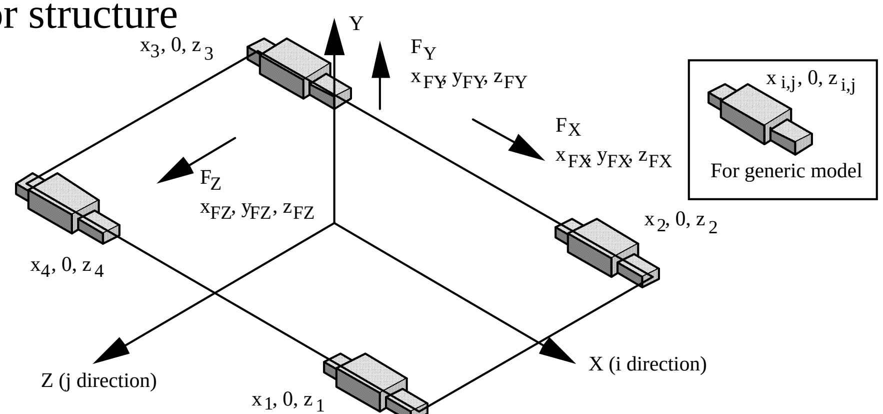
Preload

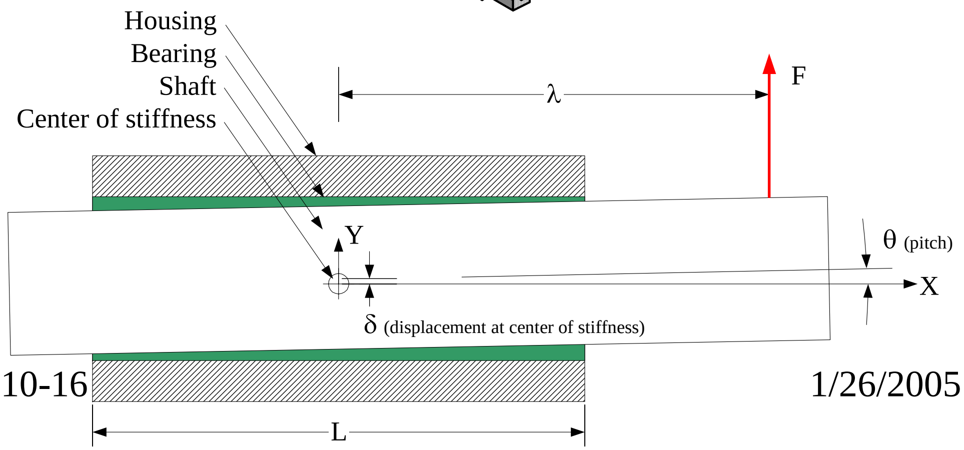


- Preload allows for bi-directional loading
  - If not careful, it can lead to over-constraint
- Preload maximizes stiffness
- Preload deflection is small, so preload can be lost by manufacturing error or wear
  - Preload loss via wear is avoided with the use of spring loaded preload systems
- Spring preloading allows dimension variations without a large change in preload force
  - Use springs or deformation of the bearings and/or structure

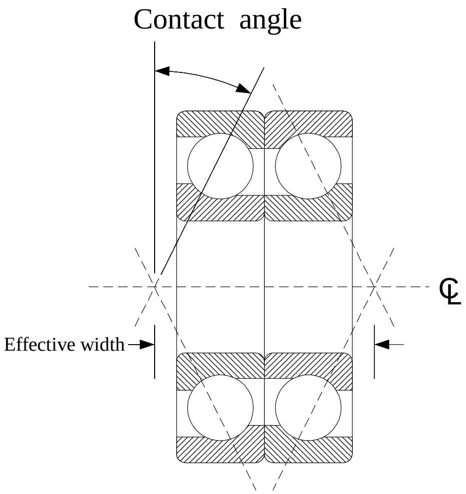


Bearings just touching rail | Bearings preloaded | Carriage fully loaded

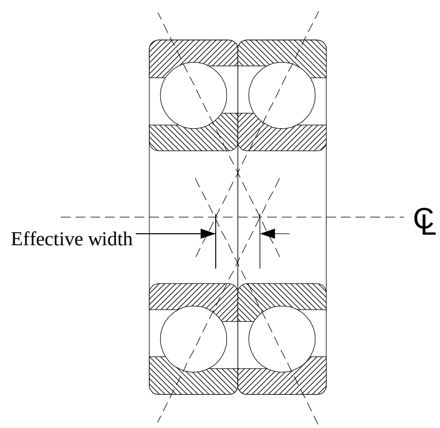




Preload: *Rolling Elements*

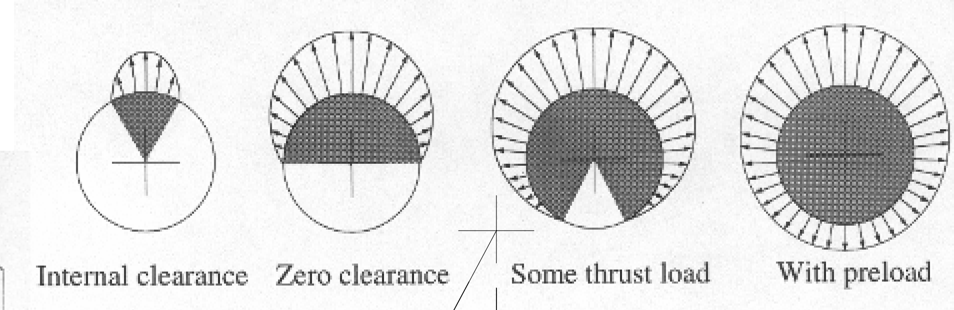


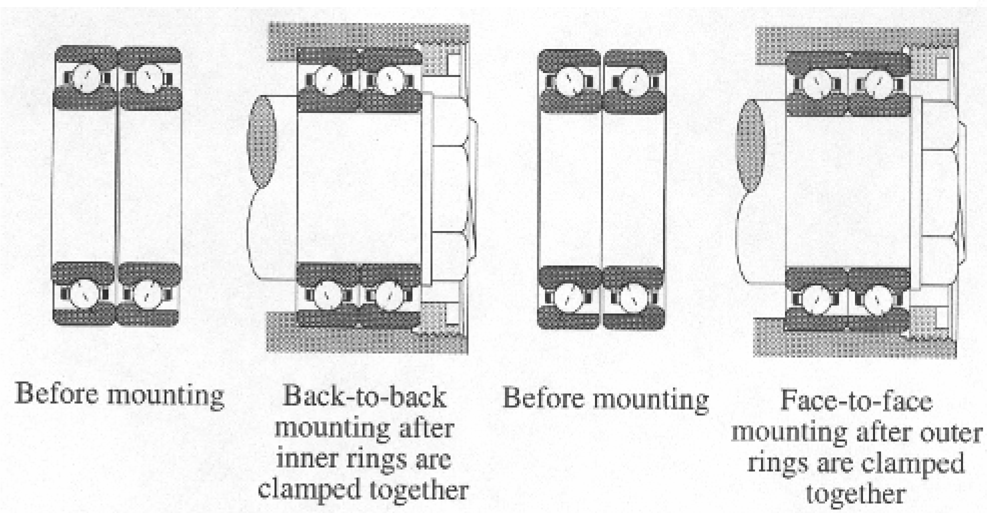
Back-to-back bearing mounting

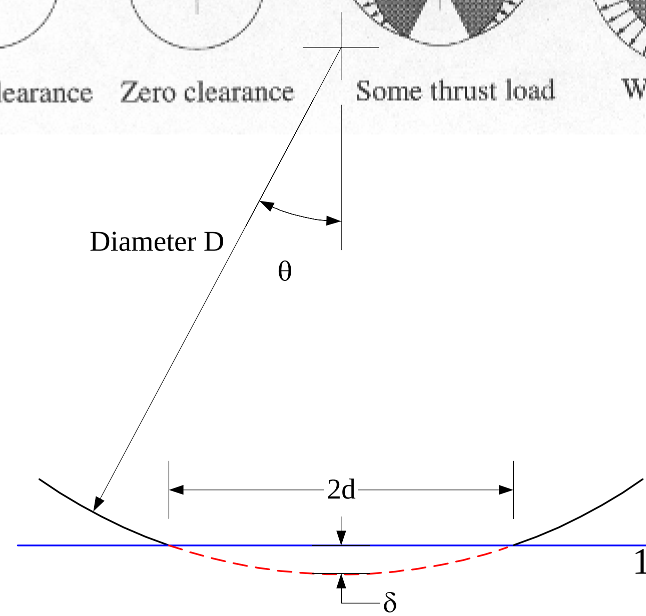


Face-to-face bearing mounting

- In order to maximize stiffness and resistance to impact loads, rolling element bearings must be "preloaded"
  - All the rolling elements must be under load, often one element loaded against another
  - When preloaded, even the rolling elements "in tension" act as springs to provide stiffness







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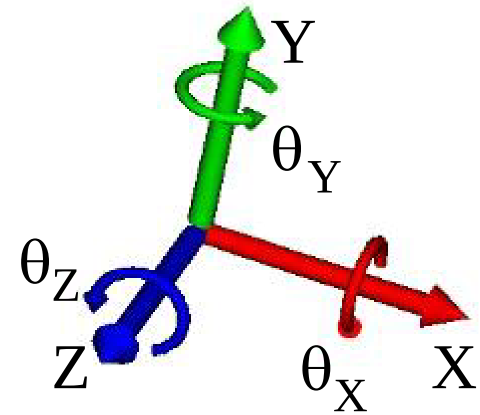
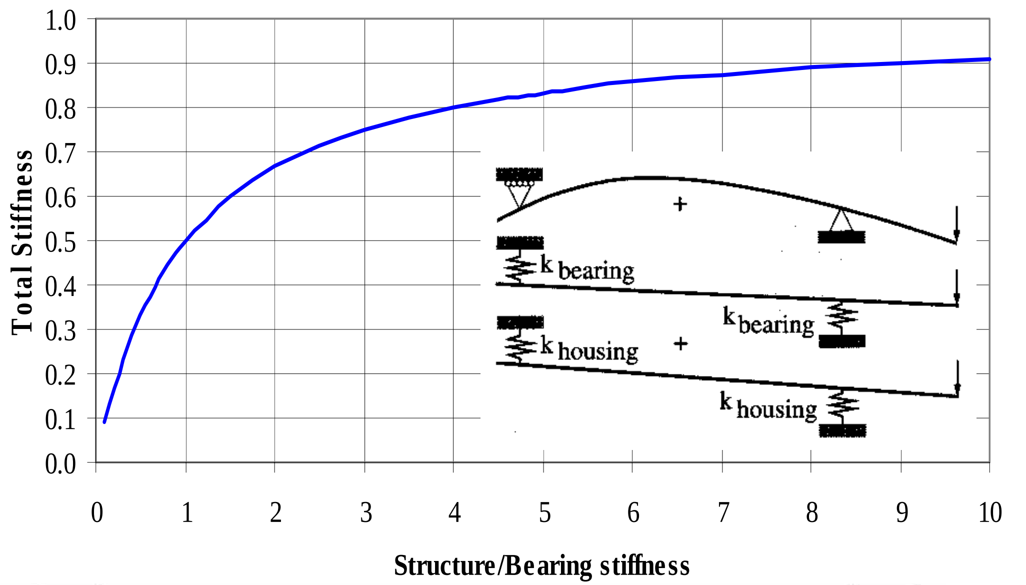
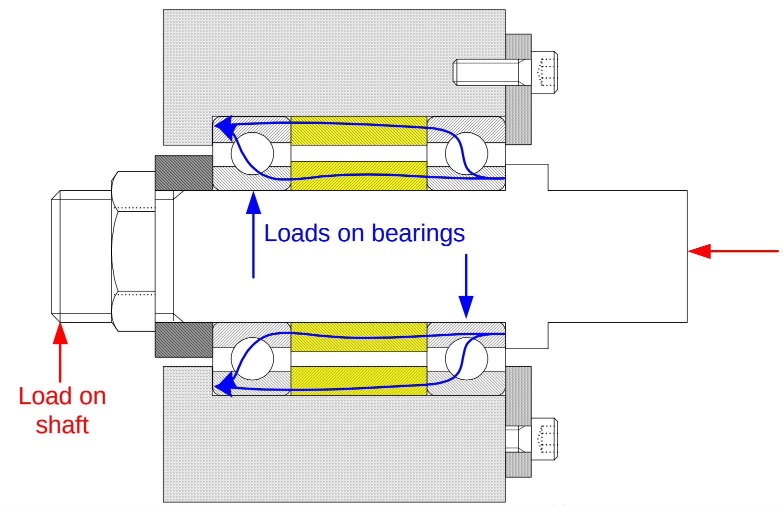
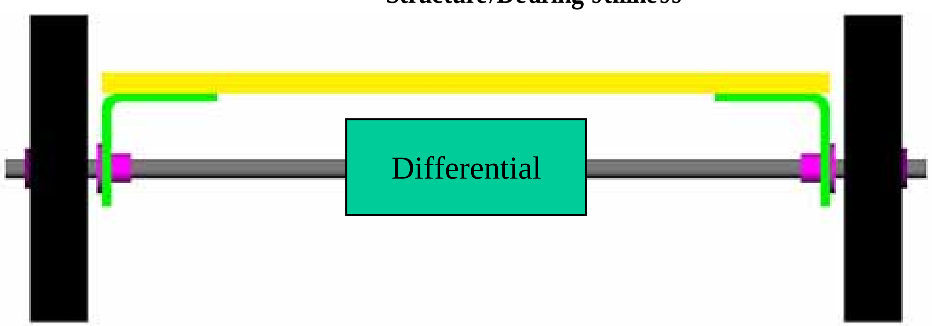
Mounting

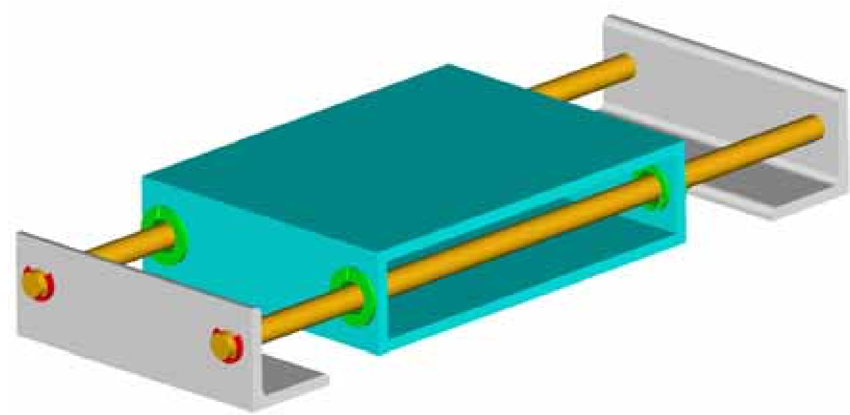


- *Exact Constraint Design:* The number constraint points should be equal to the number of degrees of freedom to be constrained
  - ***If deformations occur in your machine, will the bearings be overloaded?***
- Do a sensitivity analysis and base design decisions on analysis or experiments

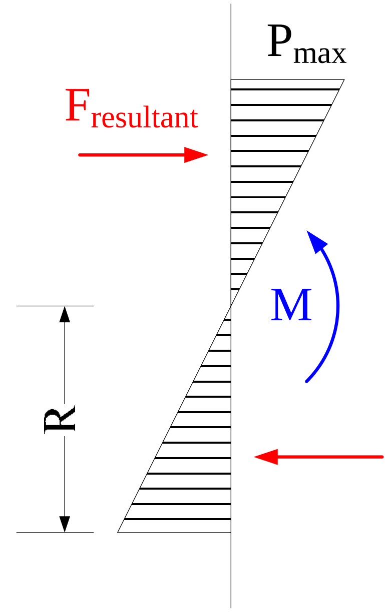




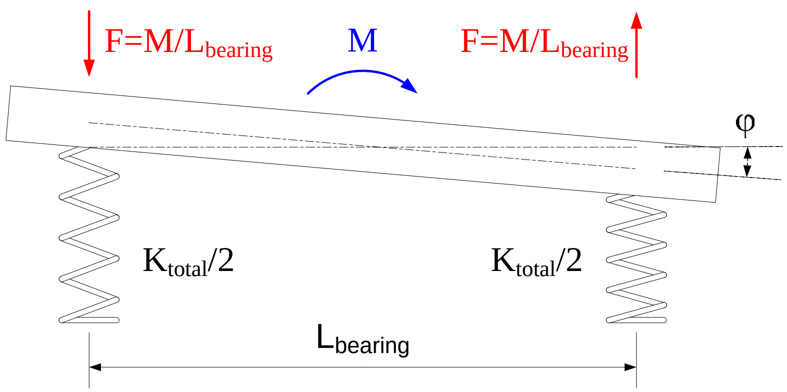




Mounting: *System Stiffness*

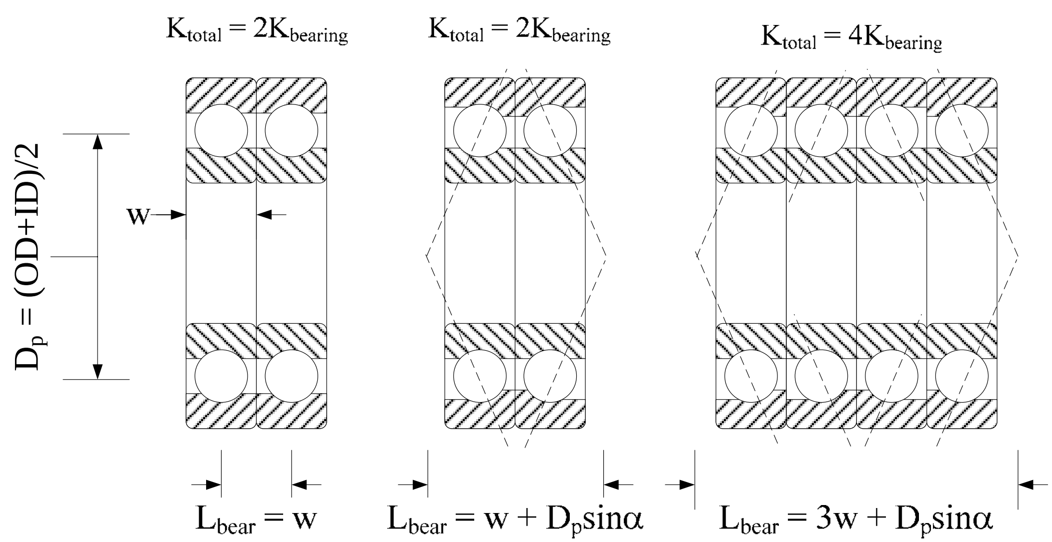


- Angular (tilt) stiffness can be estimated from lateral stiffness and bearing spacing
  - Angular misalignments are the most troublesome
  - Small misalignments can create very large bearing loads in stiff systems
- Springs modeling the system components are loaded by misalignment displacements
  - The resulting forces are added to the component loads for life calculations



$$F = \frac{M}{L_{bearing}} \qquad \delta = \frac{F}{k_{total}/2} = \frac{2M}{k_{total} L_{bearing}}$$

$$\varphi = \frac{\delta}{L_{bearing}/2} = \frac{4M}{k_{total} L_{bearing}^2} \Rightarrow k_{angular} = \frac{k_{total} L_{bearing}^2}{4}$$



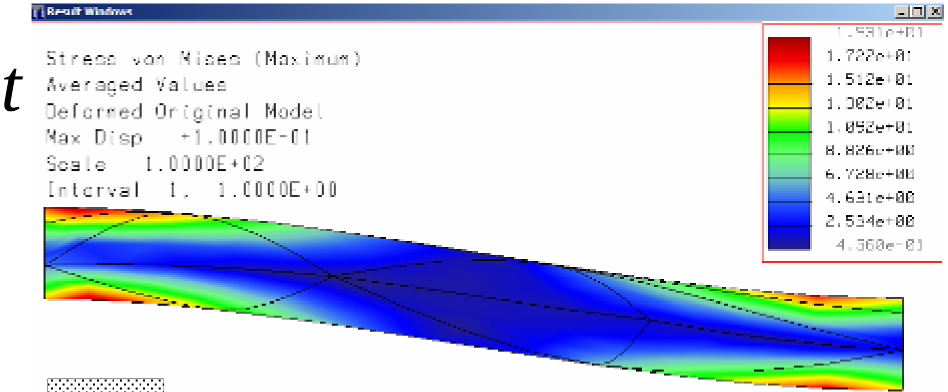
Deep Groove Pair

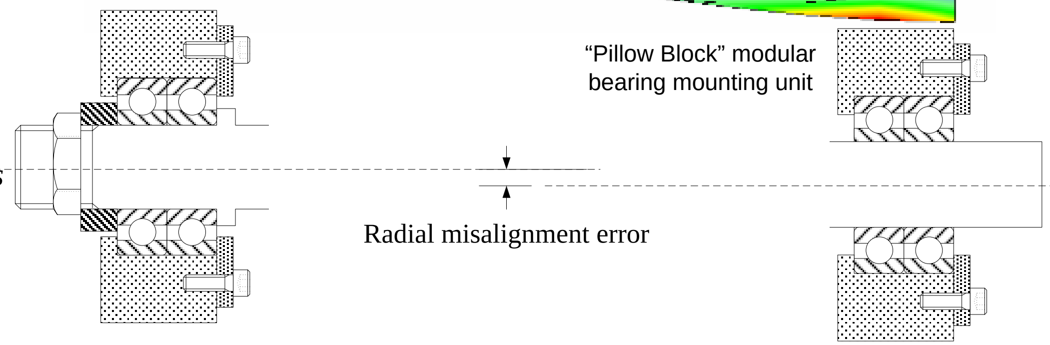
Angular Contact Back-to-back Duplex pair

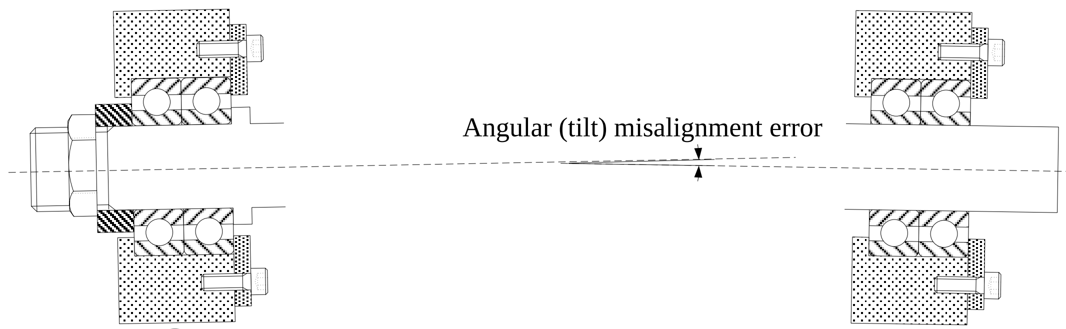
Angular Contact Back-to-Back Quad set

Mounting: *Shaft Misalignment*

- Radial and angular misalignment errors can be major contributors to total bearing loading!
  - Springs-in-series models can be used to determine bearing loads caused by misalignment displacements, ala F = kδ
    - See the spreadsheets:
  - *Bearing_stiffness_alignment.xls*
    - *Misalignment_induced_beam_stress.xls*

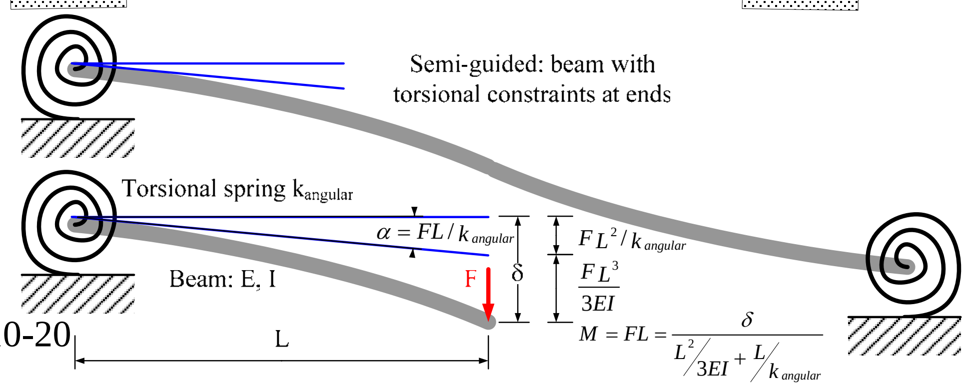






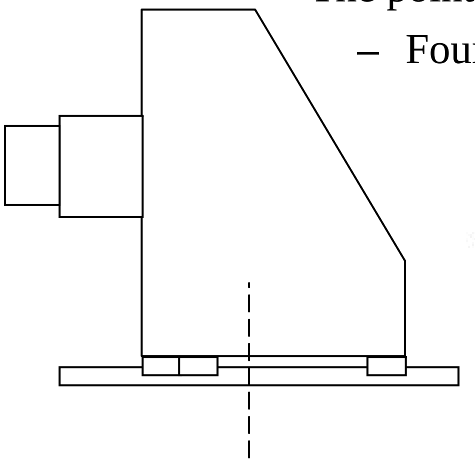
Case 1, simply supported beam (typically Nbear = Nbear2 = 1)	
Resulting moment, Mresultss (N-m)	0.360
Resulting radial forces due to misalignment	
First bearing set (N)	30
Second bearing set	30
Case 2, beam ends guided but with bearing angular compliance	
Resulting moment, Mresultbeg (N-m)	0.529
Resulting radial forces due to misalignment	
First bearing set (N)	44
Second bearing set	44
Case 3, beam ends guided but assume ZERO bearing angular compliance	
Resulting moment, Mresultbeg (N-m)	12.0
Resulting radial forces due to misalignment	
First bearing set (N)	997
Second bearing set	997

Misalignment (displacement) delta only	
Both ends guided	
Force at ends, F (N)	40.6
Moment at ends, M (N-mm)	2031
Stress at ends (N/mm^2)	20.7
Cantilevered	
Force at ends, Fc (N)	10.2
Moment at base, Mc (N-mm)	1015
Stress at base (N/mm^2)	10.3

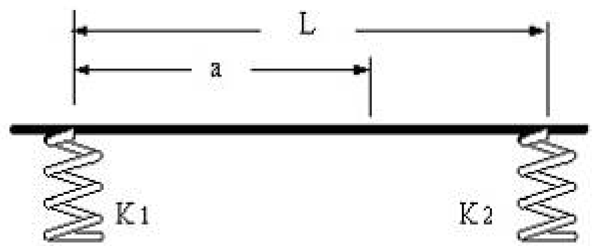


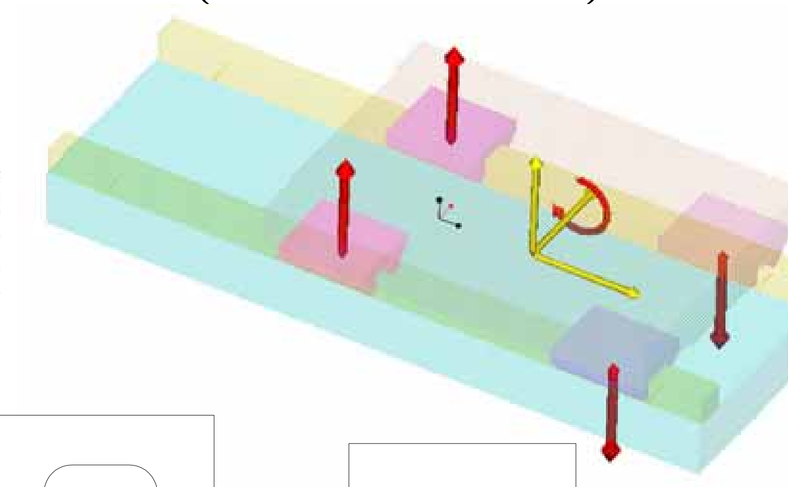
Mounting: *Centers of Action*

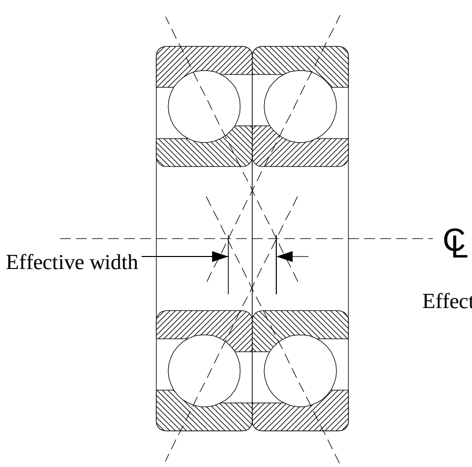
- A body behaves as if all its mass is concentrated at its ***center of mass***
- A body supported by bearings, acts about its ***center of stiffness*** *(there can be several in an axis…)*
  - The point at which when a force is applied to a axis, no angular motion occurs
    - The point about which angular motion occurs when forces are applied elsewhere
      - Found using a center-of-mass type of calculation (K is substituted for M)



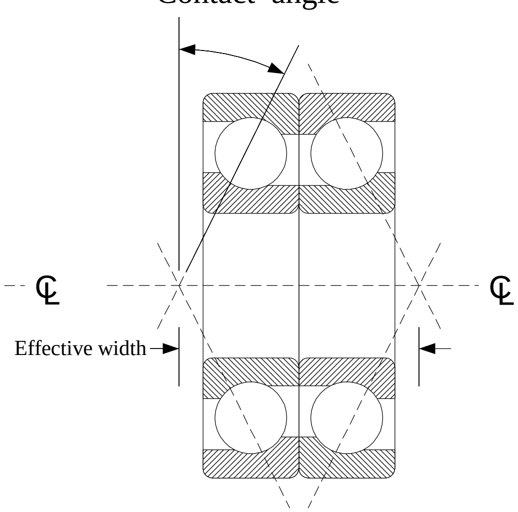
center of stiffness axis



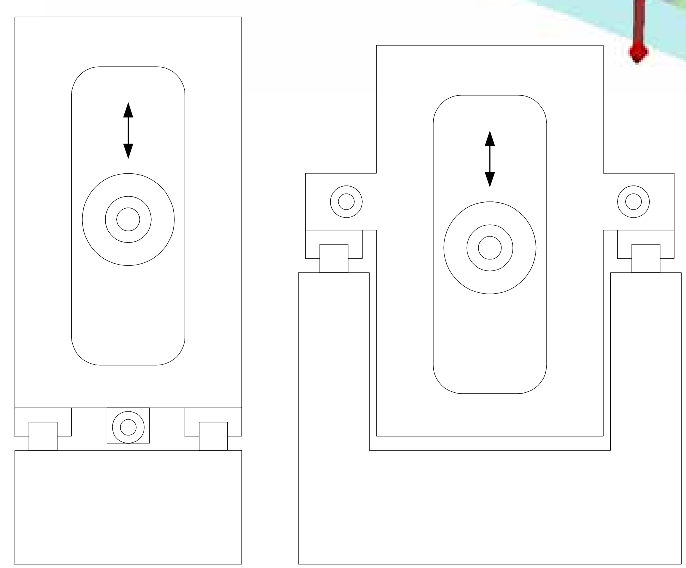


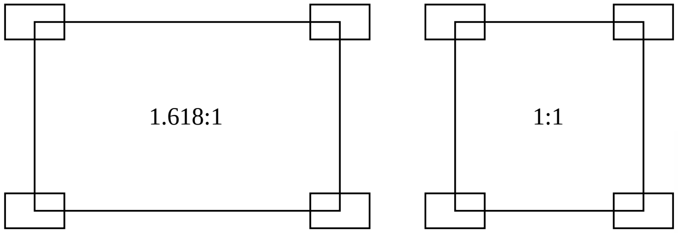


Face-to-face bearing mounting



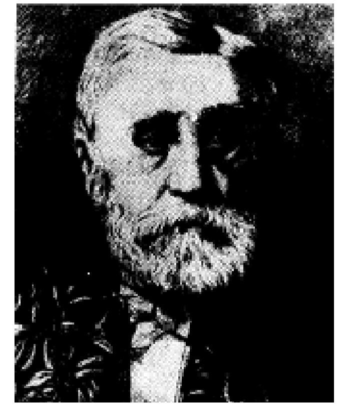
Back-to-back bearing mounting

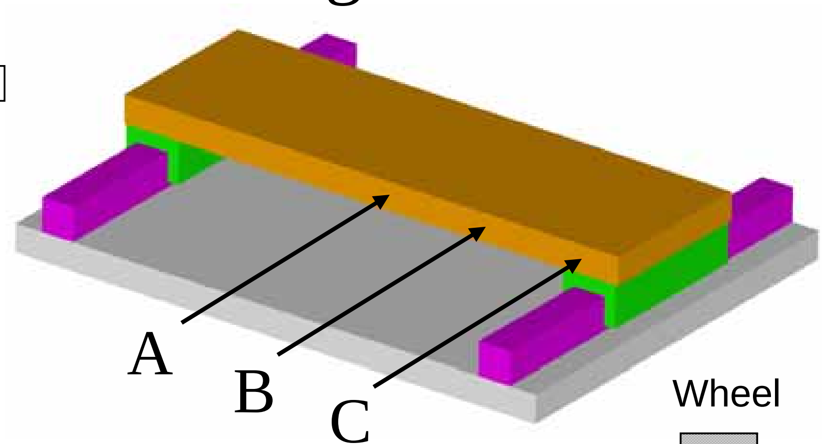




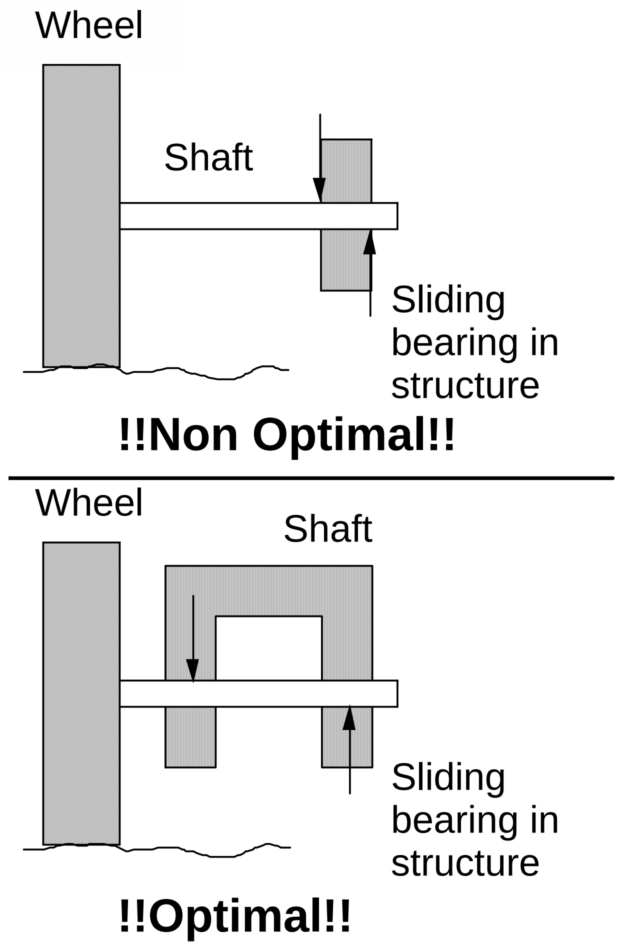
Barré de Saint-Venant 1797-1886

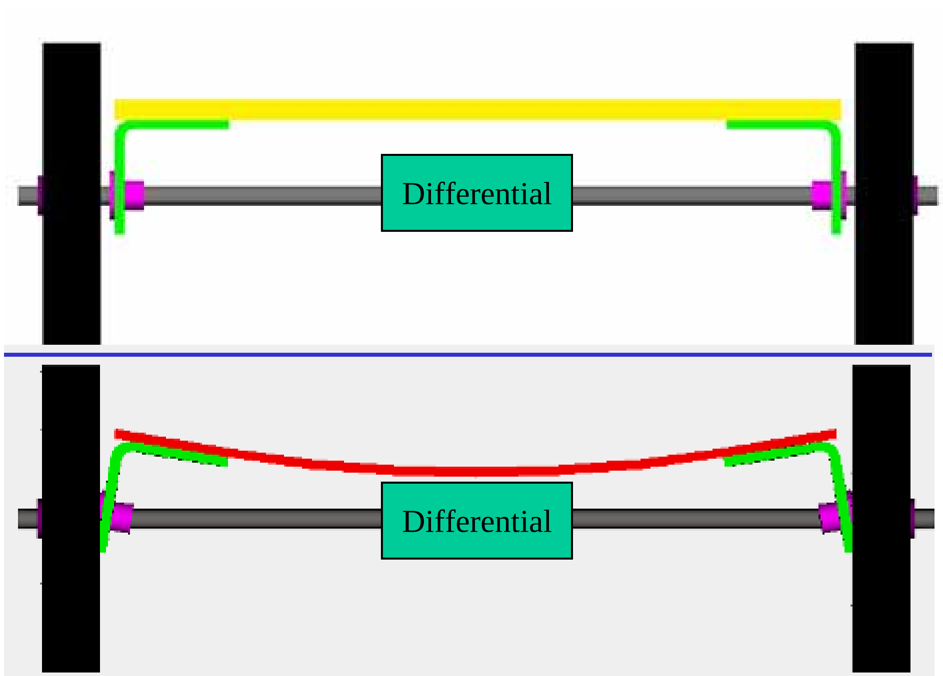
Mounting: *Saint-Venant*



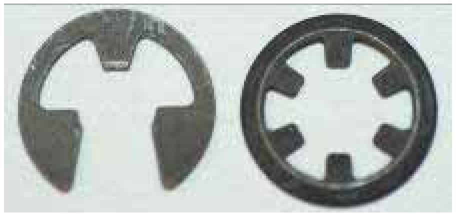


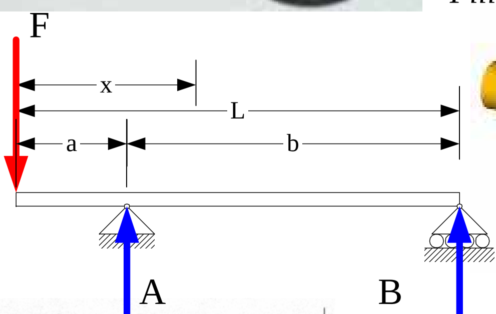
- St. Venant: Linear Bearings:
  - L/D>1
  - 1.6:1 very good
  - 3:1 as good as it gets
- St. Venant: Rotary Bearings:
  - $L_{shaft}/L_{bearing\ spacing} < 1$ and the shaft can be cantilevered
  - $L_{shaft}/L_{bearing\ spacing} > 3\text{-}5$ and the slope from shaft bending might overload the bearings, so provide adequate clearance

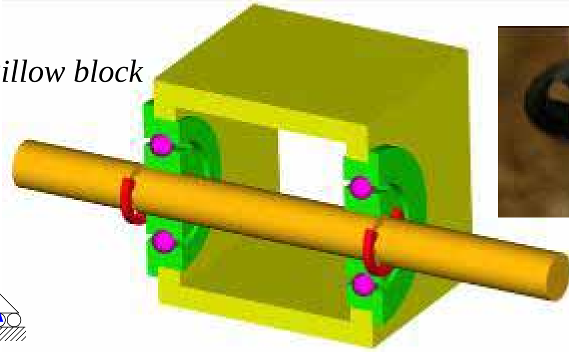


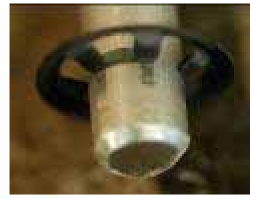


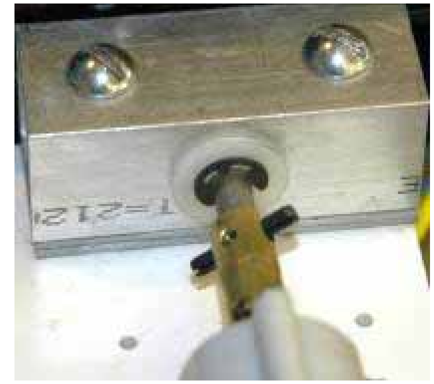
Mounting: *Rotary Motion*

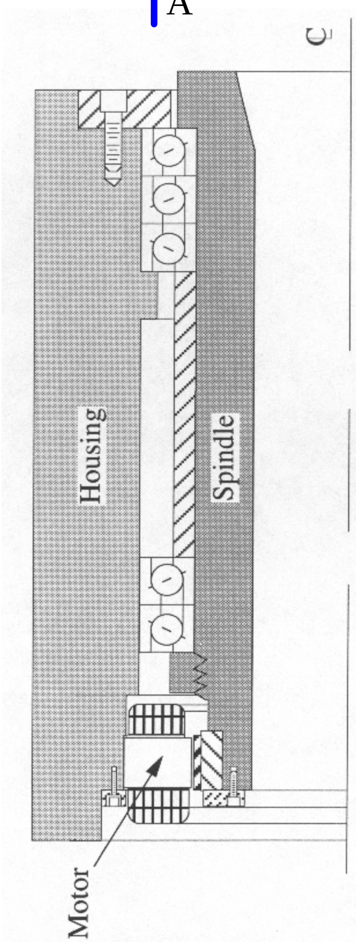




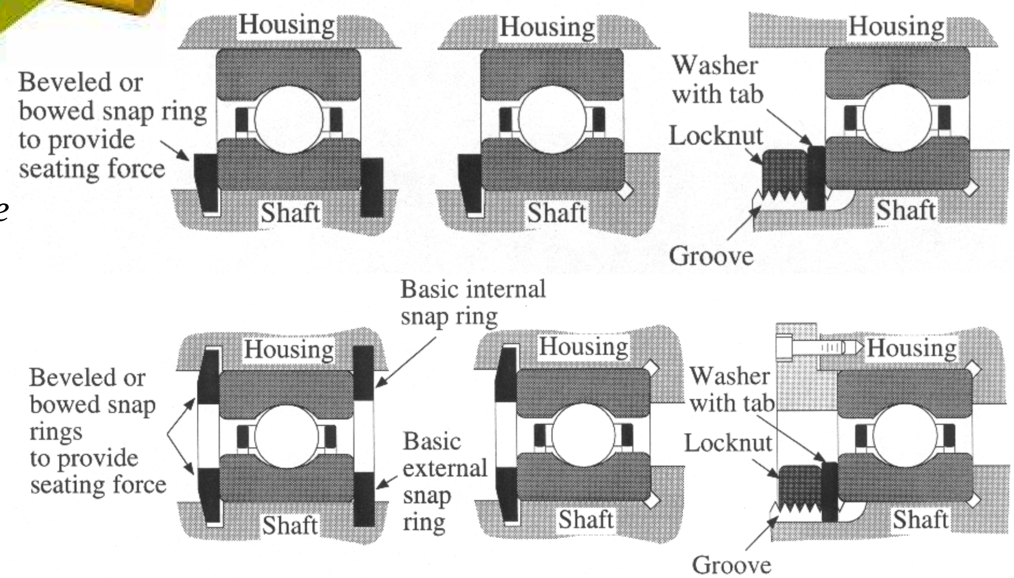


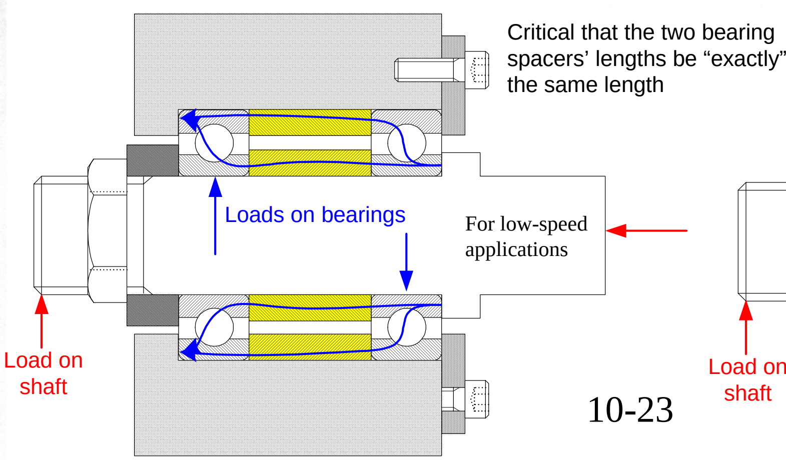


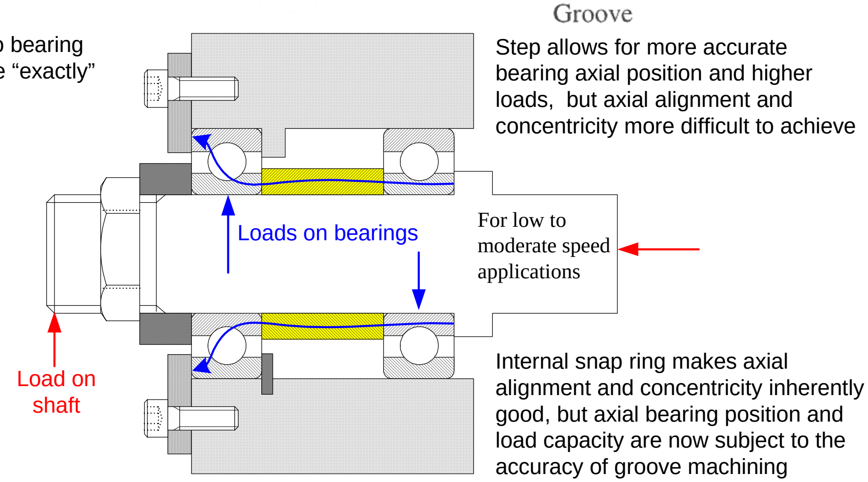




- Rotary motion bearings' *inner races* are mounted to a *shaft*, and the *outer races* fit in a *bore*
- Every rotary motion axis has one large degree of freedom, and five small error motions
- 5 degrees of freedom are typically constrained with one thrust bearing and two radial bearings

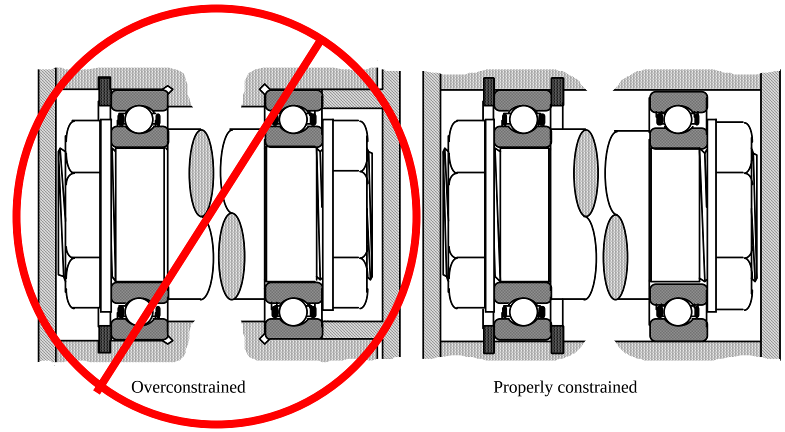


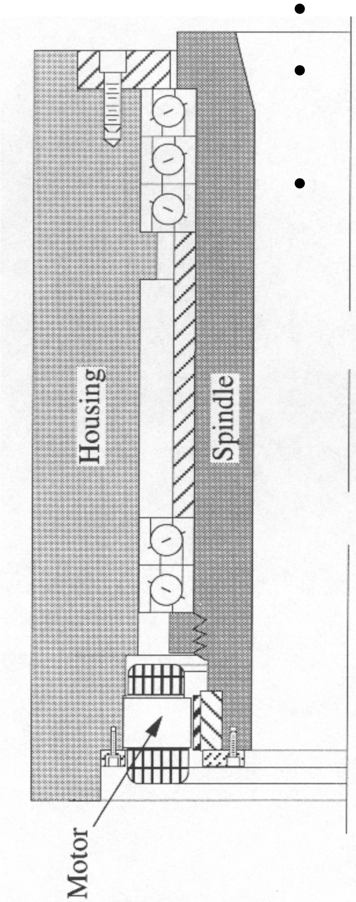


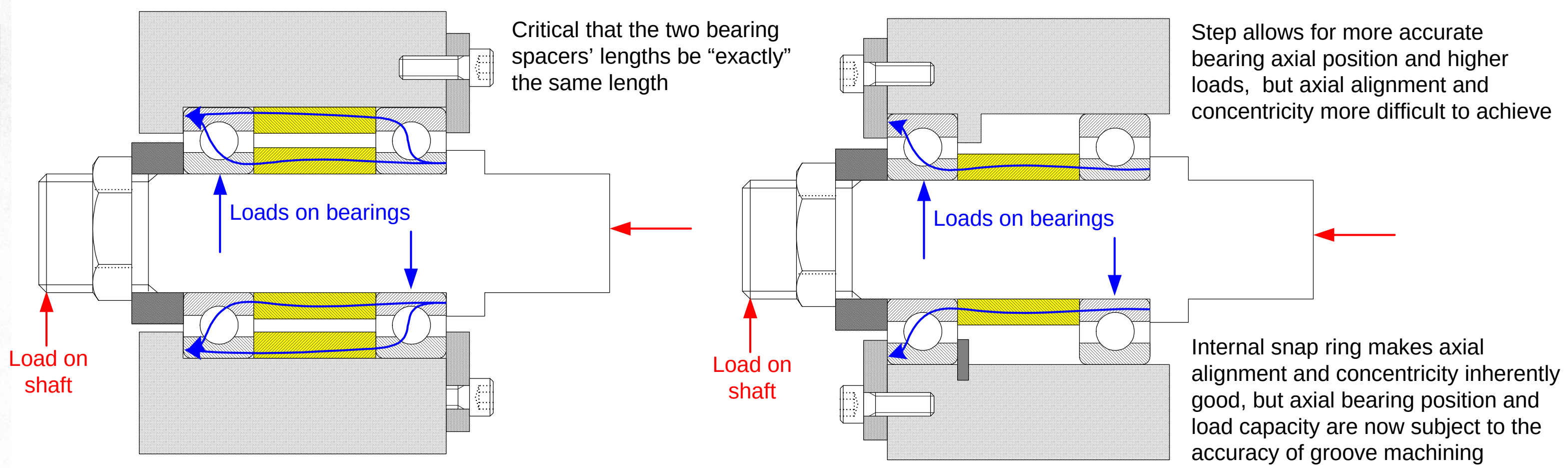


Mounting: *Thermocentric Design*

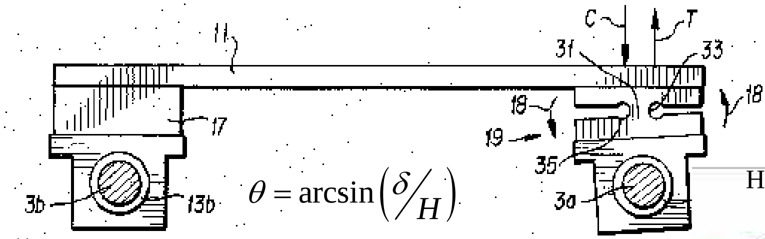
- Thermal growth can cause overconstarint and overloading
- primarily a rotary motion bearing issue
- Linear bearings, particular in large systems such as cranes and big machine tools, can also be affected
- When is a design thermally stable?
- Can deep groove bearings be mounted in a back-to-back configuration?
- What does this do to the load path?





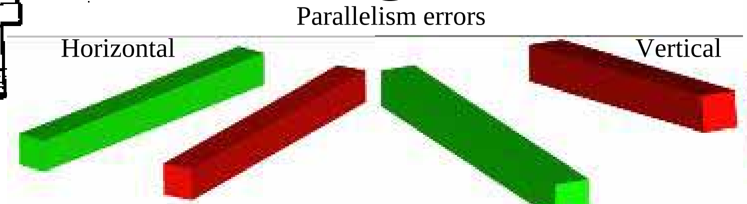


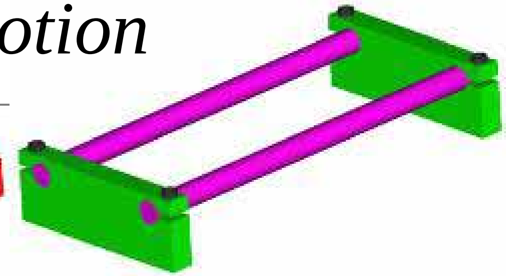
Mounting: *Linear Motion*



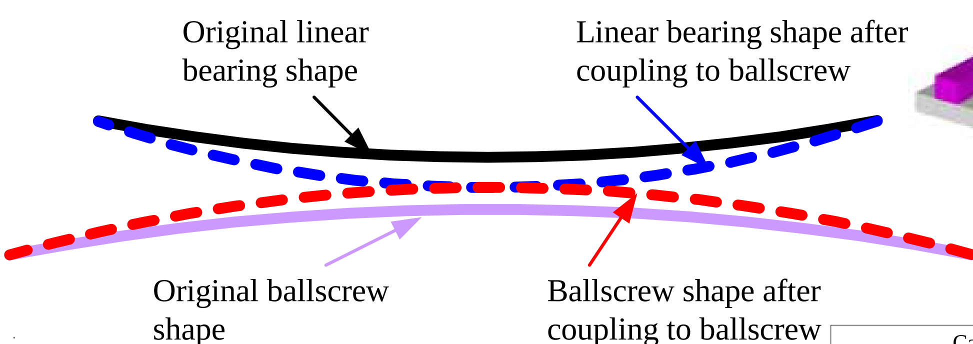
$$\theta = \arcsin\left(\delta/H\right)$$

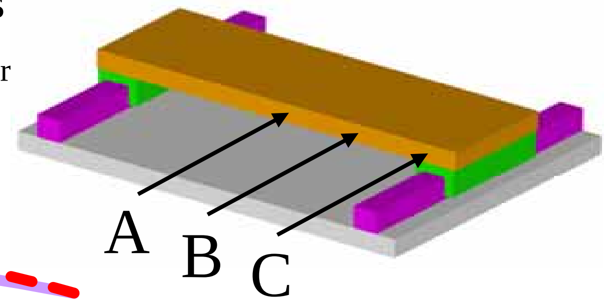
$$\Delta = H\left(1-\cos\theta\right) \approx \frac{\delta^2}{2H}$$

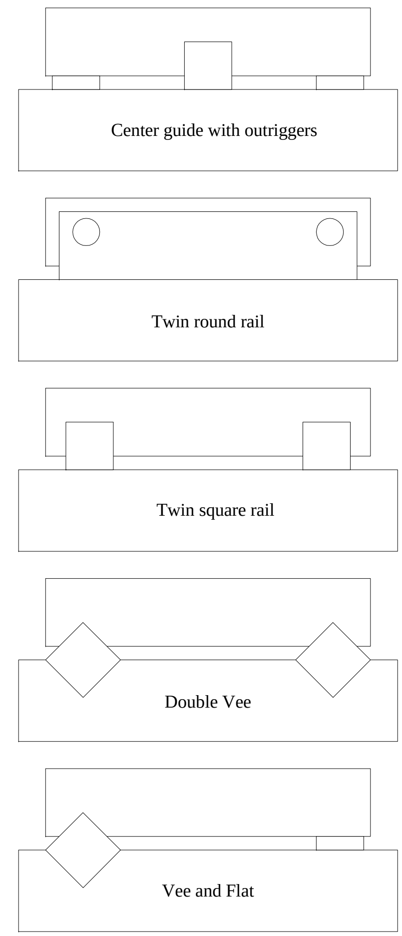


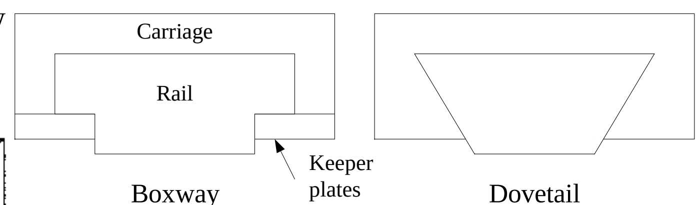


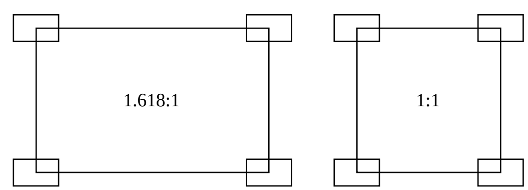
- Every linear motion axis has one large degree of freedom, and five small error motions
  - 5 degrees of freedom are typically constrained with various forms of bearing surfaces
  - Typical preloaded machine tool carriages have pairs of preloaded bearing pads in vertical and horizontal directions at each of 4 corners

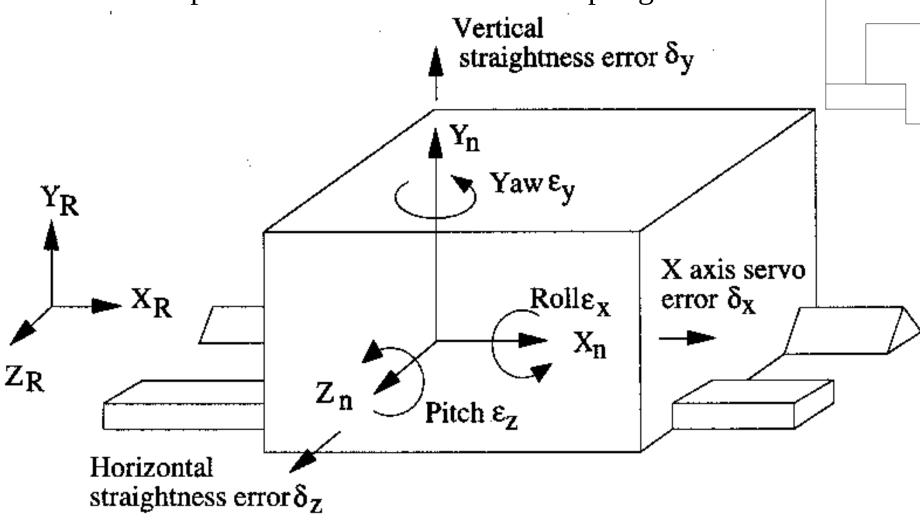








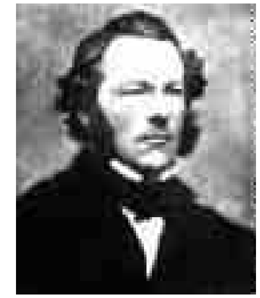




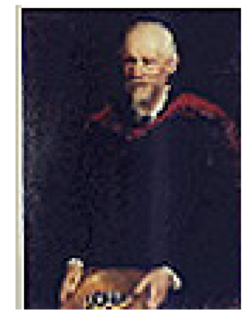
Loads, Lube & Life

- Loading:
  - The maximum load is the load the bearing can withstand for short periods
  - Longer life is achieved with lower loads
- Lubrication: *Tribology* is the study of lubrication and wear
  - Separates the structural materials, and prevents chemical bonding
  - Allows for viscous shear of a fluid thereby reducing material wear
  - Oil is common ; Grease is soap that holds oil and releases it as it warms
  - Lubricants attract dirt, so less is typically better, and use seals if possible
  - Surface finish is critical!
- Oil impregnated bearings release lubricant as they get warm
- Some materials are inherently lubricious and function “dry”

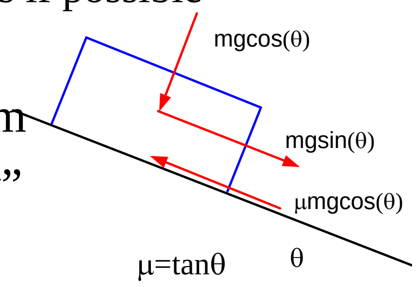
Claude Louis Marie Henri Navier (1785-1836)

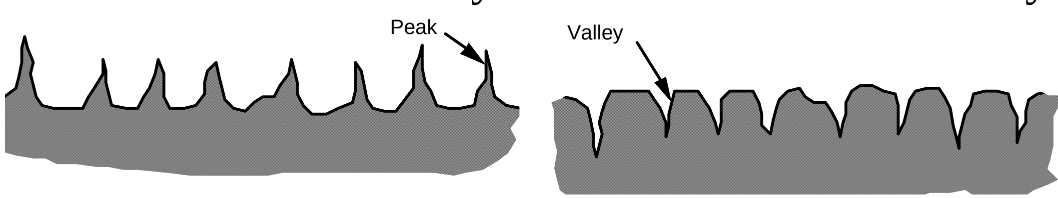


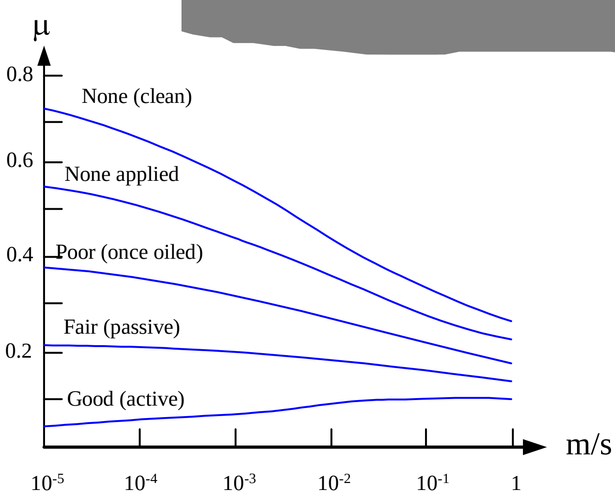
George Gabriel Stokes (1819-1903)

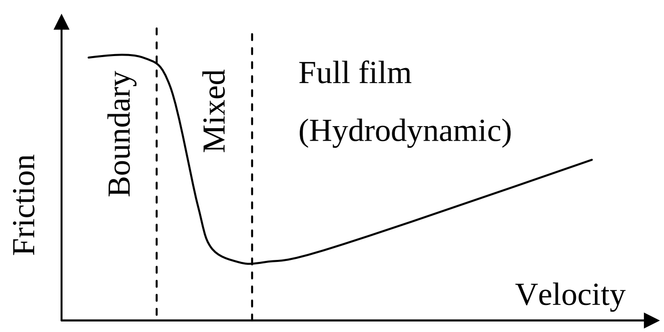


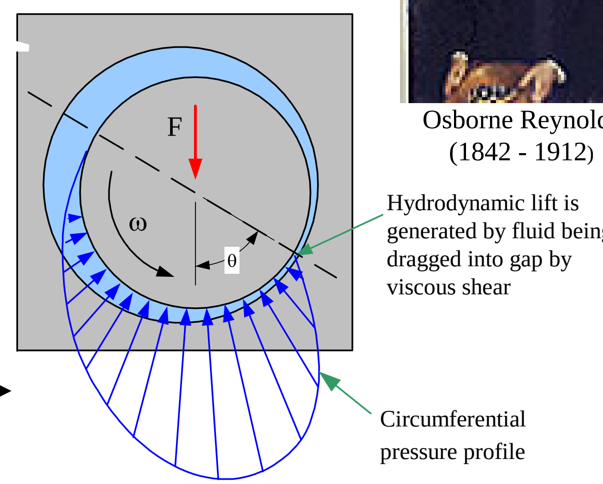
Osborne Reynolds (1842 - 1912)



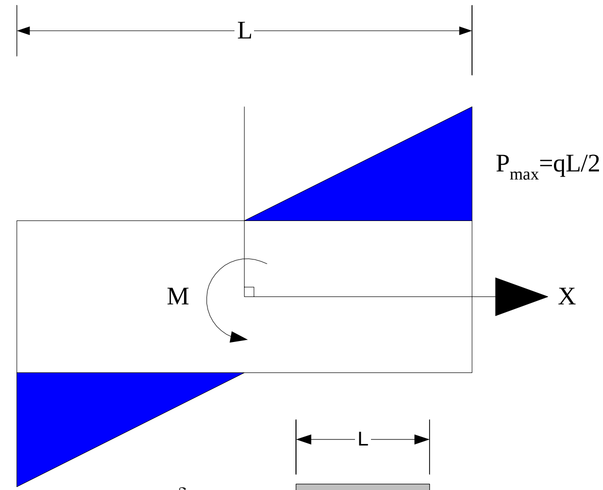








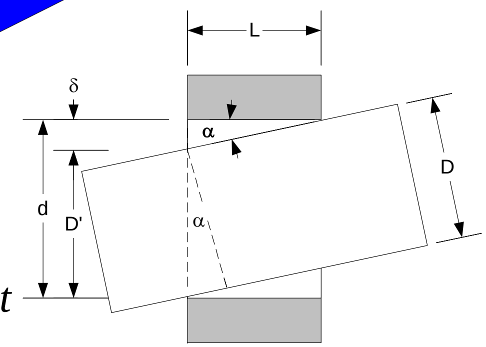
Loads, Lube & Life: *Sliding Contact*

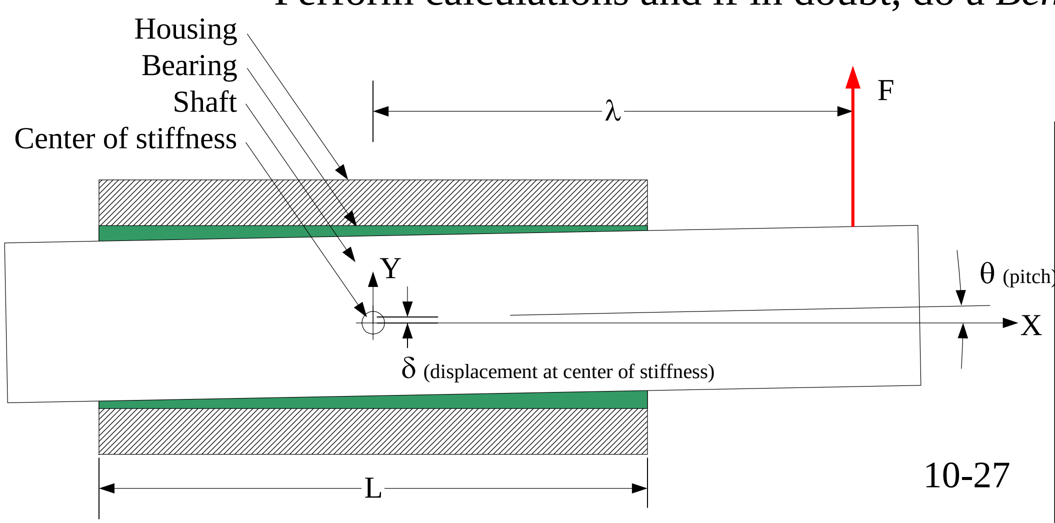


- The PV value is the product of the pressure and the velocity
- Sliding contact bearings have a maximum allowable pressure and a maximum PV value`
  - The allowable product of pressure (F/(D*L)) and velocity
  - The stiffness of the bearing
  - Delrin bearing used as a bushing (Nylon has ½ these values)

Maximum Pressure (N/mm^2, psi)	**140**	**19,895**
PV continuous (N/mm^2-mm/s, psi-ips)	**1800**	**9,791**
PV short periods (N/mm^2-mm/s, psi-ips)	**3500**	**19,581**
Compressive Modulus (GPa, psi)	**4**	**579,710**

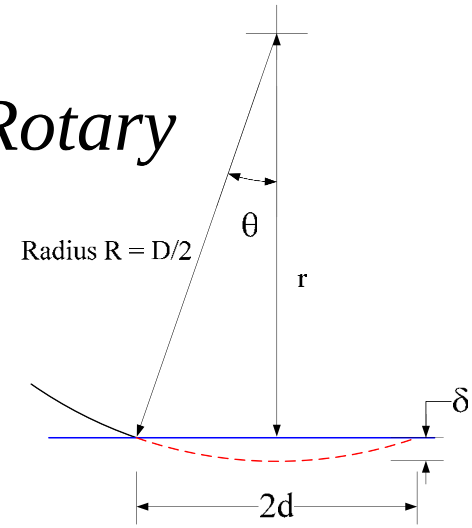
  - http://www.dupont.com/enggpolymers/americas/products/deldata.html
    - Perform calculations and if in doubt, do a *Bench Level Experiment*



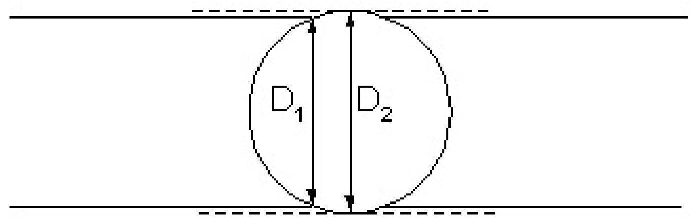


Bearing_Sliding_Pitch_PV.xls	
To determine bearing contact pressure in a slider loaded by a moment	
By Alex Slocum 3/8/98. Last modified 5/2/04 by Alex Slocum	
Enters numbers in **BOLD,** Results in **RED**	
Total slider length, L (mm)	**25**
Slider contact width, w (mm)	**10**
Pivot point height above center of stiffness, h (mm)	**25**
Force, F (N)	**100**
Max PV continuous, PVC (N/mm^2-mm/s)	**1800**
Moment, M (N-mm)	**2500**
Maximum contact pressure, qmax (N/mm^2)	**2.400**
Speed, v (mm/sec)	**50**
PV (N/mm^2-mm/sec)	**120**

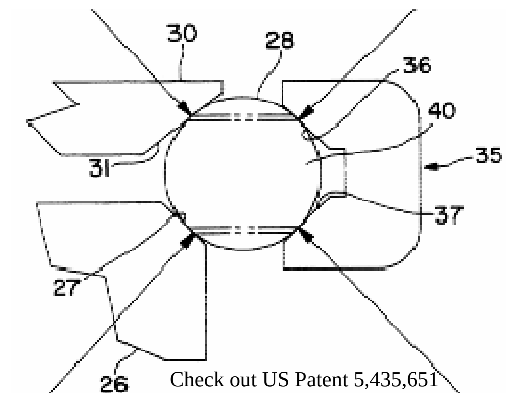
Loads, Lube & Life: *Rolling Contact Rotary*



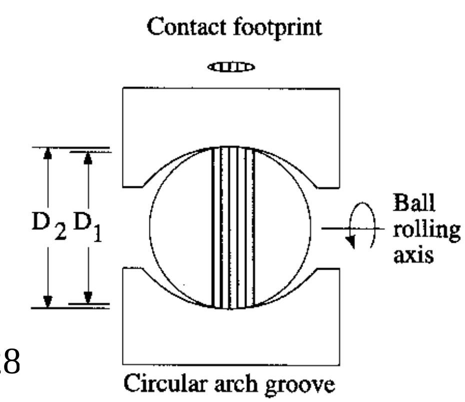
- Rolling contacts have friction because the elements deform under load and cause rolling across different effective diameters (slip)

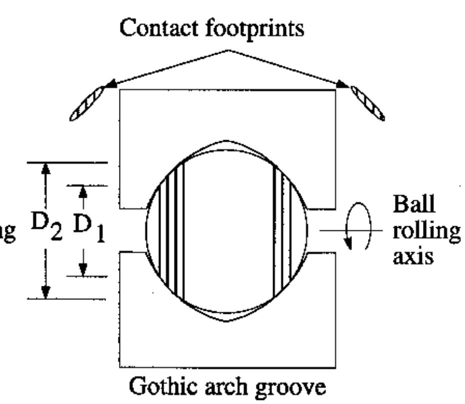


  - The rolling bearing pulls in lubricant, whose viscosity increases with pressure, to form an *elastohydrodynamic* lubrication layer between the ball and the race
    - The EHD layer accommodates the differential slip, but generates heat via viscous shear
- The rolling contact interface geometry also plays a significant role



Check out US Patent 5,435,651 (www.uspto.gov). How does it use rolling slip to create differential motion and a transmission effect?

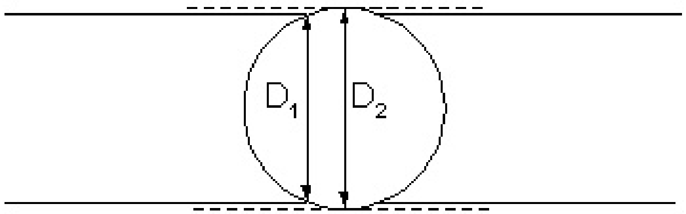




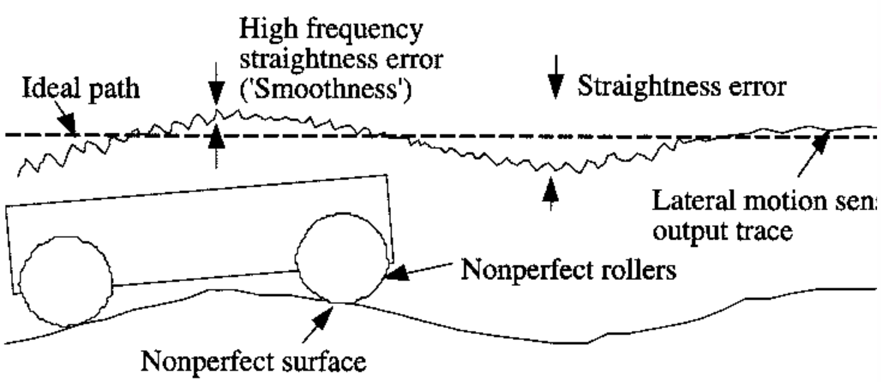
© 2000 Alexander Slocum

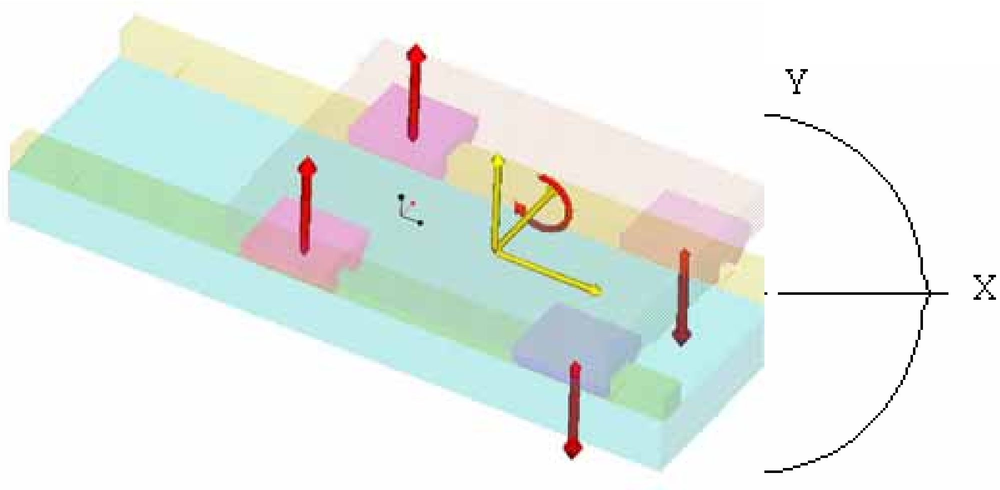
Loads, Lube & Life: *Rolling Contact Linear*

- Rolling contacts have friction because the elements deform under load and cause rolling across different effective diameters (slip)



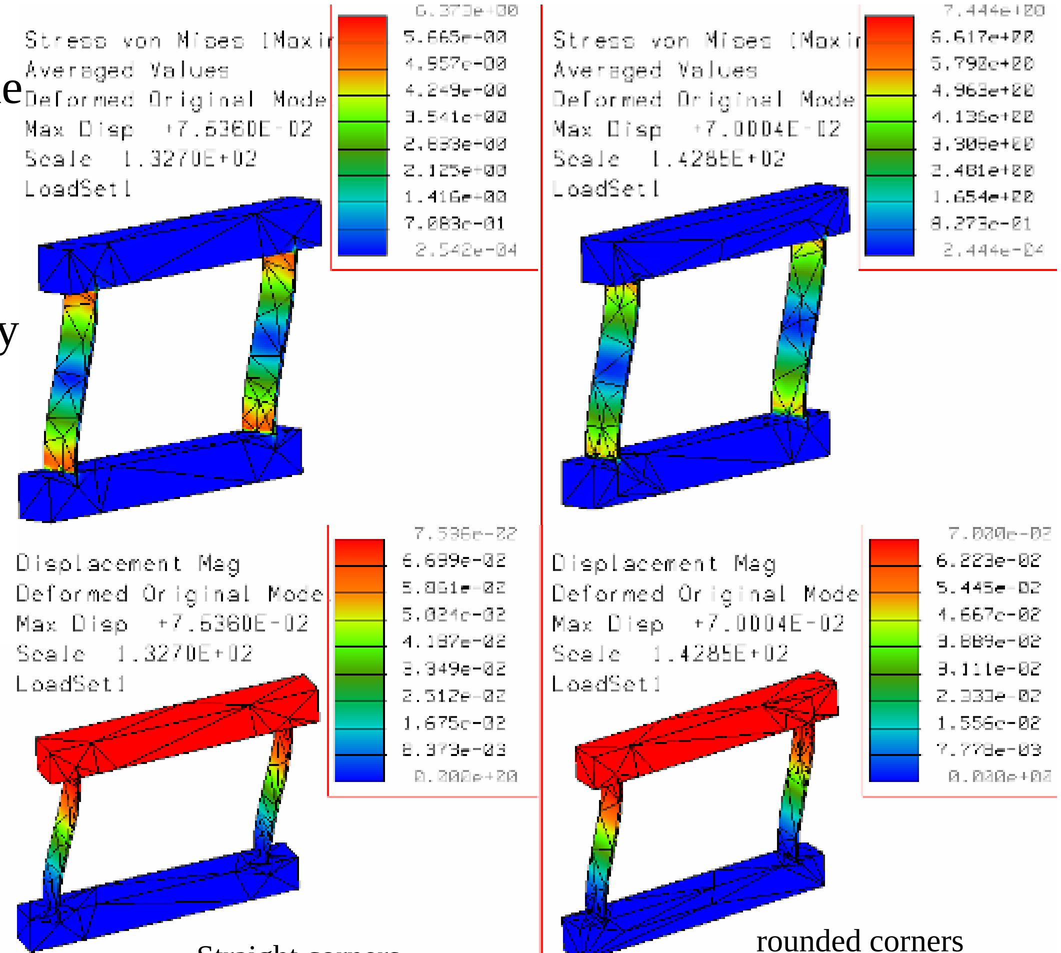
  - The rolling bearing pulls in lubricant, whose viscosity increases with pressure, to form an *elastohydrodynamic* lubrication layer between the ball and the race
    - The EHD layer accommodates the differential slip, but generates heat via viscous shear
- The rolling contact interface geometry also plays a significant role





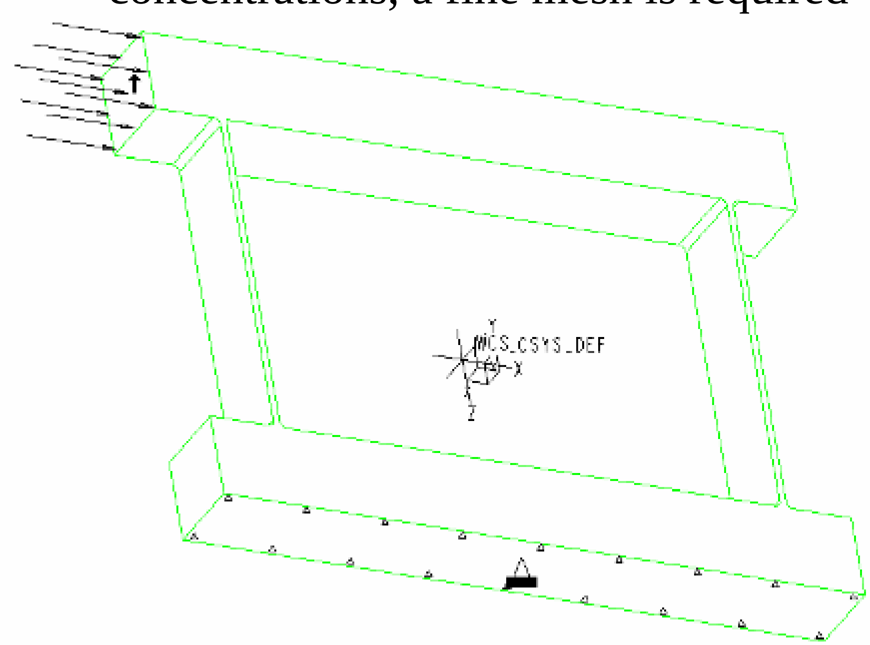
Loads, (no) Lube & Life : *Flexures*

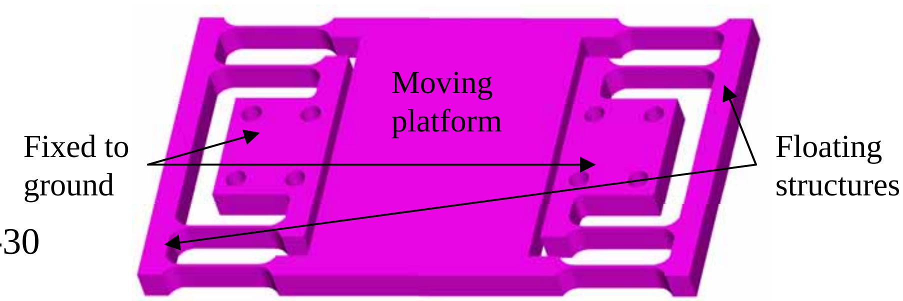
- To reduce stress, use rounds equal to the blade thickness; however, this reduces the effective blade length by one blade thickness
- Spreadsheets allow a designer to rapidly develop designs
- Once a design is developed, it can be checked with Finite Element Analysis
- For FEA to accurately predict stress concentrations, a fine mesh is required



Straight corners

rounded corners
(r = blade thickness)





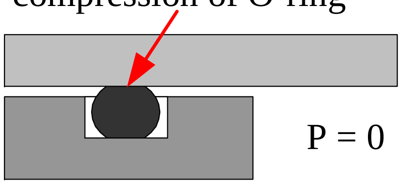
http://nmml.afsc.noaa.gov/education/pinnipeds/seals.htm

Folks, use good seals and keep the environment clean!

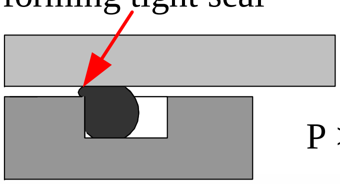
Dynamic Seals

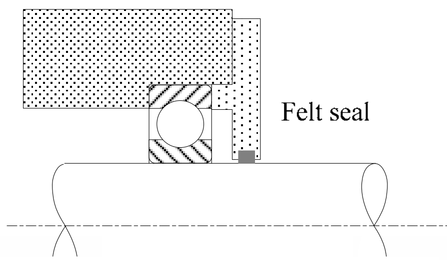
- Keeping dirt out of a bearing is of utmost importance for long bearing life
- The simplest seals are shields that keep dirt out using a labyrinth path
  - Internally supplied air pressure create a net outflow
- A mechanical contact seal is the best for low speed sealing, but it generates friction
- *Flingers* use centrifugal force to keep contaminants out and lubricants in

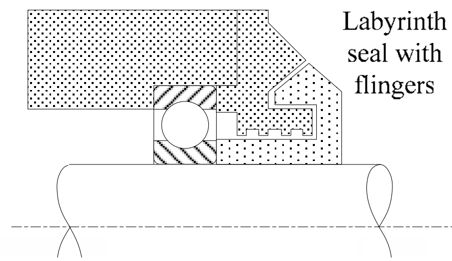
Initial installation compression of O-ring



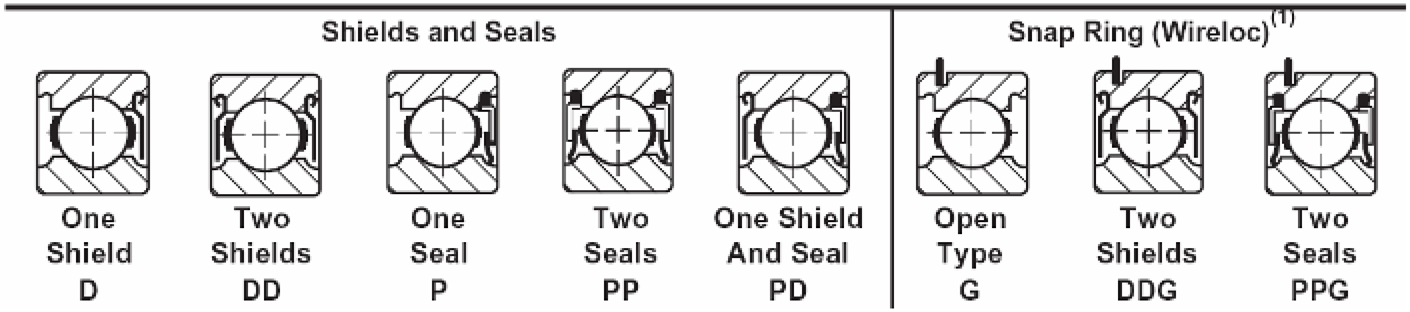
"Extrusion" of O-ring forming tight seal



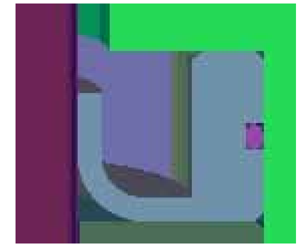




SHIELDS, SEALS AND SNAP RING COMBINATIONS



http://www.timken.com/industries/torrington/catalog/pdf/fafnir/radial.pdf

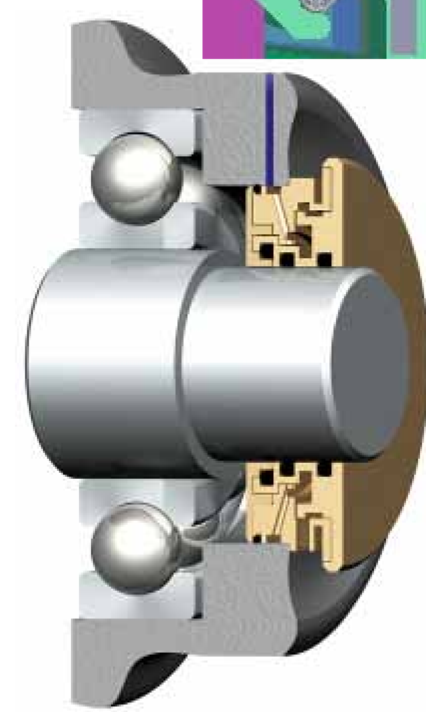


FlexiLip™

FlexiSeal™

Oil Seal

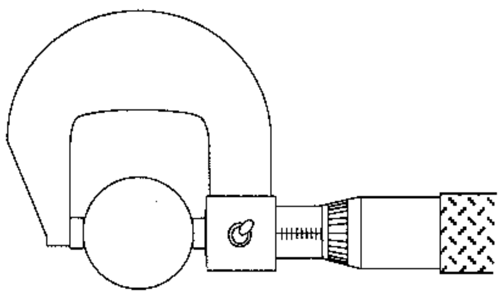
http://www.parker.com/sg/indexv4.asp

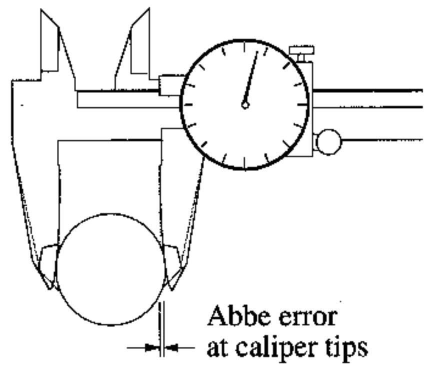


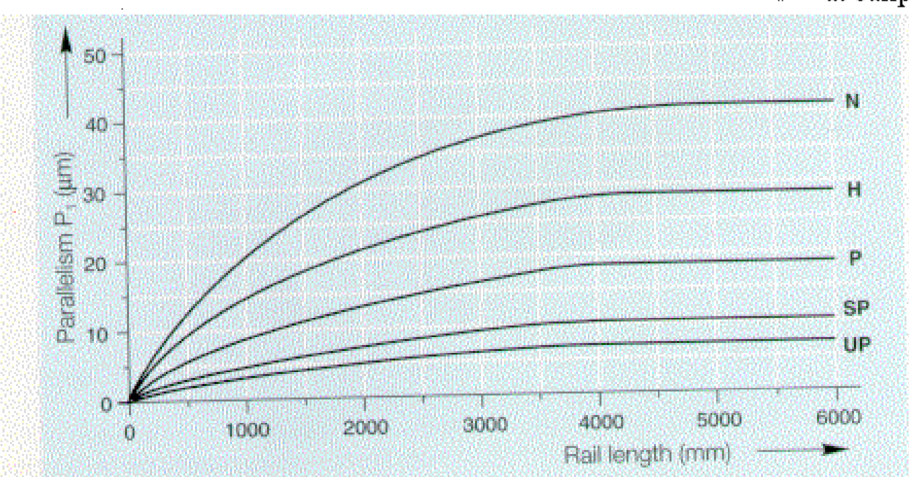
http://www.inpro-seal.com

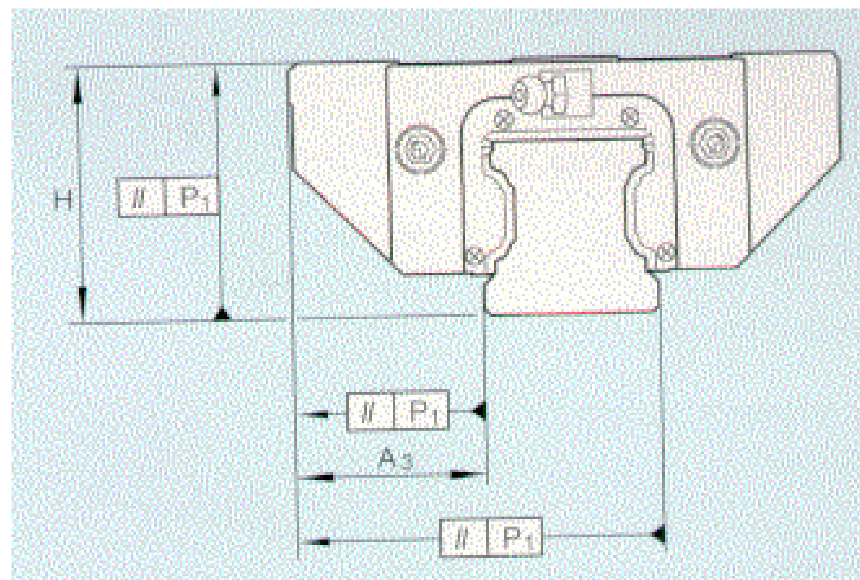
Error Motions

- Bearings are not perfect, and when they move, errors occur in their motion
  - Accuracy standards are known as *ABEC* classes as set by the Annular Bearing Engineers Committee of the Anti-Friction Bearing Manufacturers Association, Inc. (AFBMA)
    - ABEC 3 rotary motion ball bearings are common and low cost
    - ABEC 9 rotary ball bearings are used in the highest precision machines
    - The International Standards organization (ISO) has similar standards
- Remember Abbe and sine errors and how they can amplify bearing angular errors!



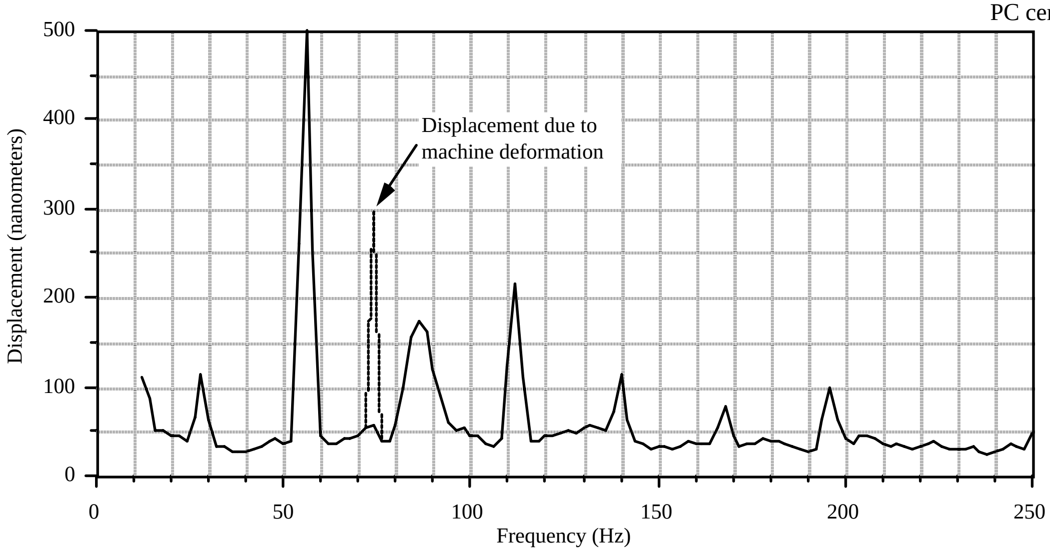


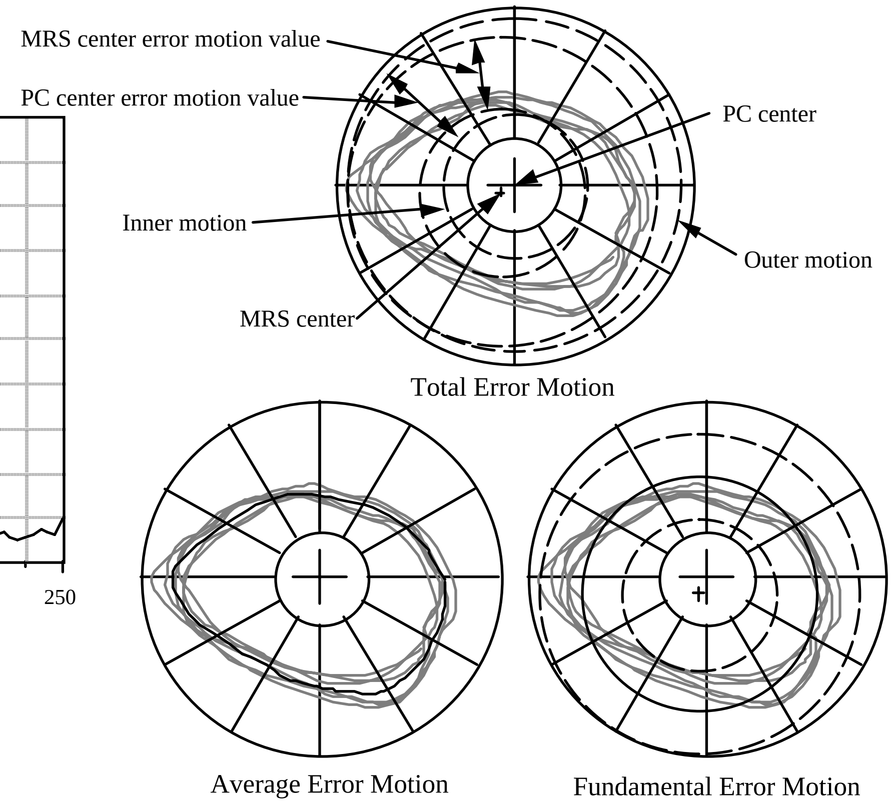




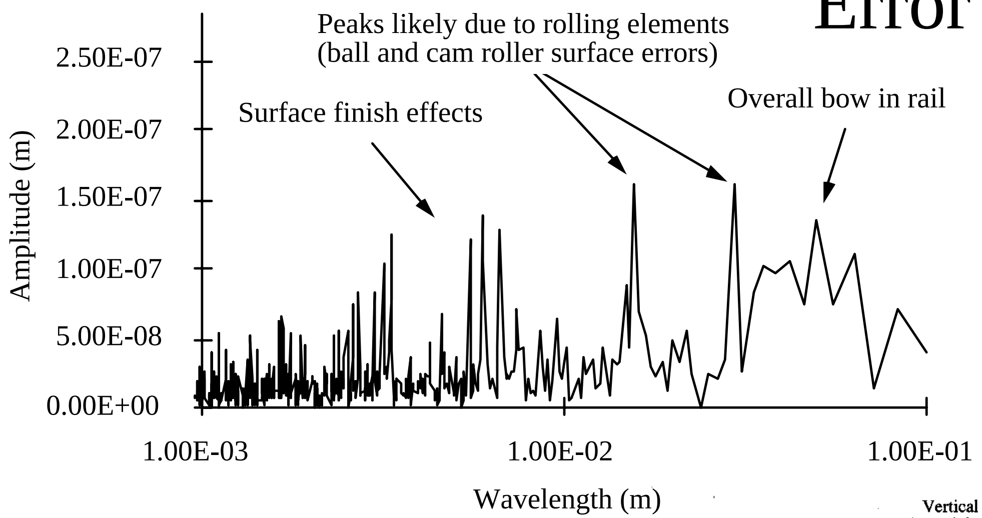
Error Motions: *Rotary Bearings*

- Disc drives exist because of accurate repeatable rotary motion bearings
  - Radial, Axial, and Tilt error motions are of concern
- Precision Machine Designers measure error motions and use *Fourier transforms* to determine what is causing the errors…
- Standards exist for measuring the errors of an *axis of rotation:*
  - Axis of Rotation: Methods for Specifying and Testing, ANSI Standard B89.3.4M-1985

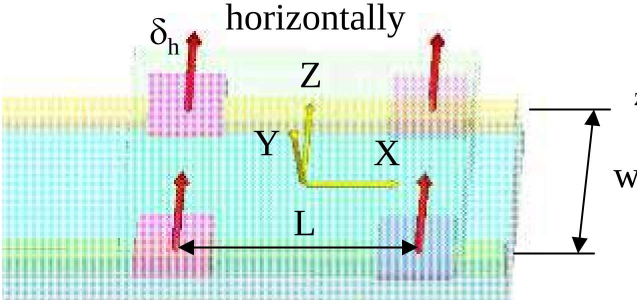




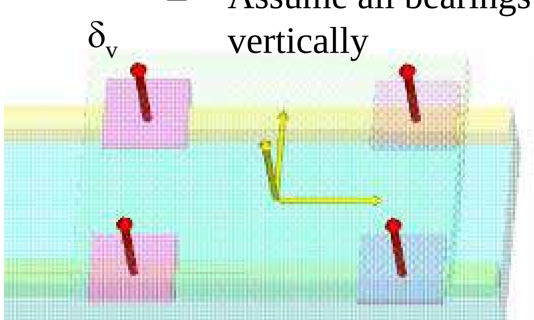
Error Motions: *Linear Bearings*

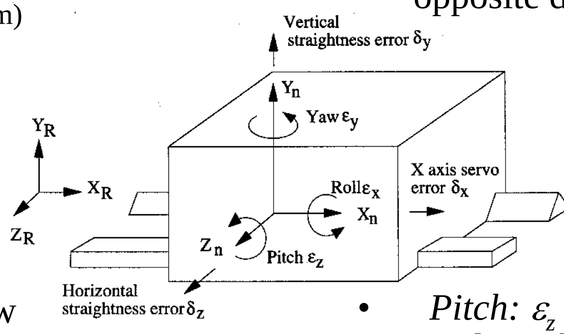


- *Horizontal Straightness:* δ_y
  - Assume all bearings move horizontally

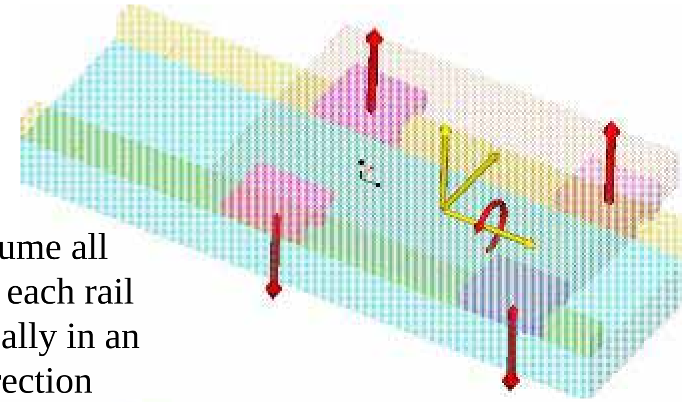


- *Vertical Straightness:* δ_z
  - Assume all bearings move vertically

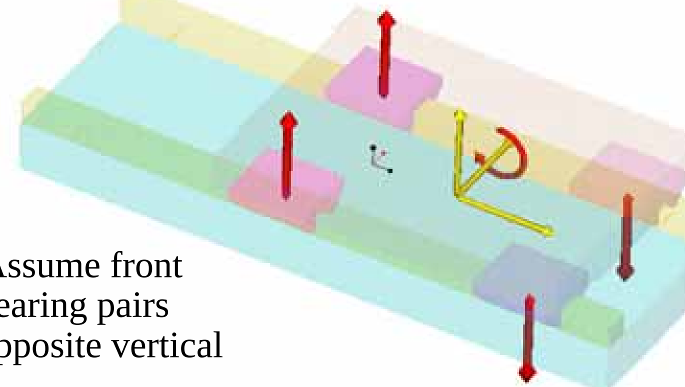




- *Roll:* ε_x Assume all bearings on each rail move vertically in an opposite direction



- *Pitch:* ε_z Assume front and rear bearing pairs move in opposite vertical directions



- *Yaw:* ε_y Assume front and rear bearing pairs move in opposite horizontal directions