Precision Machine Design

Topic 16

Rolling element linear motion bearings

Purpose:

Rolling element linear motion bearings are in large part responsible for making automation possible. From a system's perspective, they are one of the most important types of machine elements.

Outline:

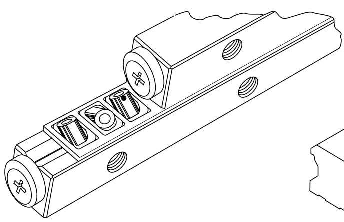
- **Introduction**
- **Characteristics of rolling element linear bearings**
- **Types of linear bearings**

"Cunning words may confound the principle of virtue. Impatience in little things may confound mighty plans."

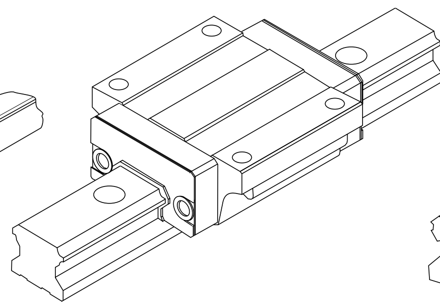
Confucius

Introduction

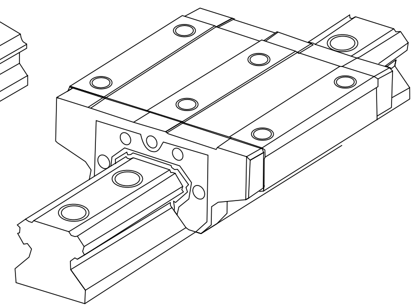
- **There are a seemingly infinite number of variations on rail geometries and ball handling methods.**
- **There are a seemingly infinite number of variations on rail geometries and roller handling methods.**
- **Typical linear rolling element bearing configurations:**



Nonrecirculating roller bearing



Recirculating ball bearing



Recirculating roller bearing

General design considerations

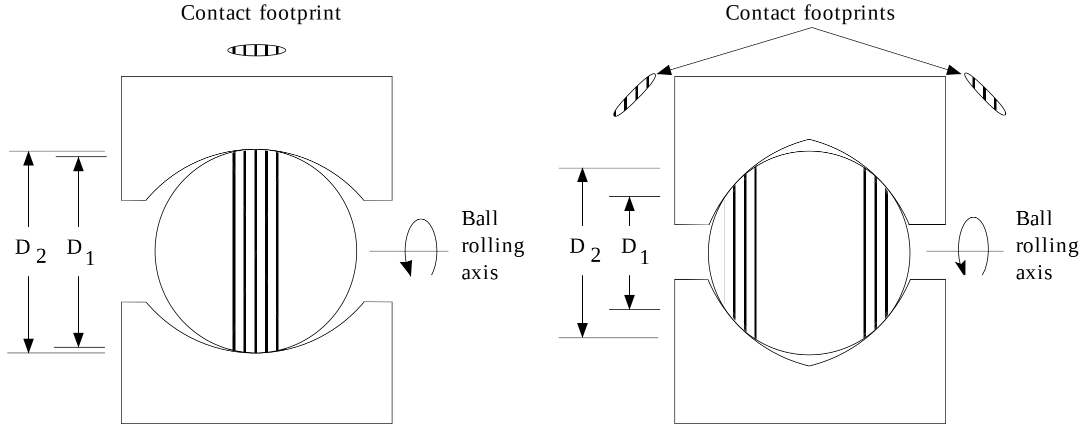
- **There are three main types of rolling element linear motion bearings:**
    - **Non-recirculating balls or rollers.**
    - **Recirculating balls.**
    - **Recirculating rollers.**
- **Before choosing a rolling element linear motion bearing, there are several fundamental issues to consider including:**
    - **Balls or rollers, which to use?**
    - **Shape of the contact surface.**
    - **To recirculate or not to recirculate?**
    - **Bearing spacing.**
    - **Selection criteria.**
- **Bear in mind many of the fine points of general characteristics of rotary motion bearings.**

Balls or rollers, which to use?

- **Balls can be made more accurate.**
- **Balls have no potential to skid sideways.**
- **Rollers typically have to have a slight barrel shape (or a slightly curved raceway) to avoid edge loading.**
- **Rollers can have greater load capacity than balls in a circular arch.**
- **In the end, all contacts are governed by the Hertz equations, and physics rules over sales talk.**
    - **Look at the specification sheets.**
    - **Look at straightness data and rolling element noise spectrums.**
    - **Build and test a system if necessary.**
- **The wise user selects interchangeable components!**

Shape of the contact surface

- **A circular arch groove typically has 3% slip during rolling compared to 40% for a Gothic arch groove:**



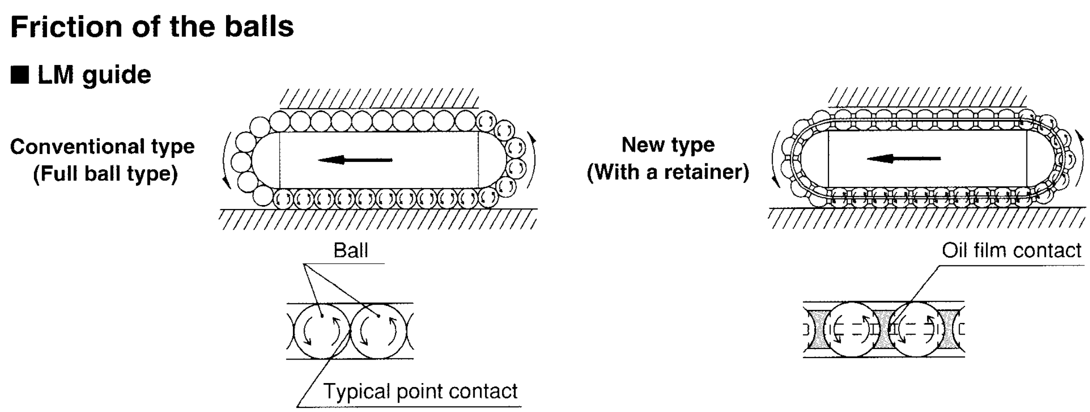
Circular arch groove

Gothic arch groove

- **The greater the contact area, the greater the damping.**
- **The greater the amount of slip, the greater the wear rate.**

To recirculate or not to recirculate?

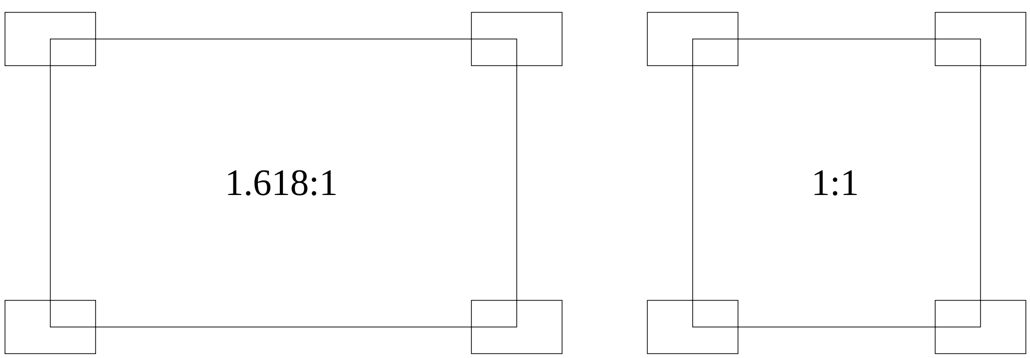
- **Recirculating elements allow for "infinite" travel.**
- **As the elements leave the raceway and enter the raceway, they generate acoustical and straightness noise.**
- **In most bearings, the elements are not retained, so they can rub on each other causing friction and noise.**
    - **THK's new patented NR series encapsulates bost of the balls in a polymer necklace that keeps the balls spaced, and helps to keep them lubricated.**



- - **This reduces rolling element noise by 50%**
  - **This increases maximum speed to up to 4 m/s**
    - **Megatool makes a roller bearing, where the rollers are connected by roller chain-like links at their ends to achieve a similar quite smooth linear bearing.**
- **Recirculating bearings are often compact and can resist loads and moments from all directions.**
- **In general, for short stroke precision applications, it is often best to use non-recirculating bearings.**

Bearing spacing

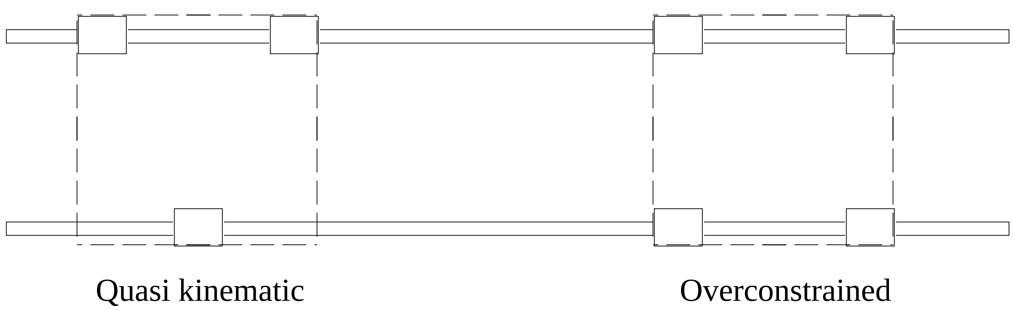
- For machine tools, typically the system will be over constrained anyway.
    - One should not always be shy about supporting a carriage at all four corners.
- The greater the ratio of the longitudinal to latitudinal (length to width) spacing:
    - The smoother the linear motion will be and the less the chance of walking (yaw error)
- First try to design the system so the ratio of the longitudinal to latitudinal spacing of bearing elements is about 2:1.
- For the space conscious, the bearing elements can lie on the perimeter of a golden rectangle (ratio about 1.618:1).
- The minimum length to width ratio is 1:1 to minimize yaw error.



- The higher the speed, the higher the length to width ratio should be.
- For large moving bridge machines:
    - It is often necessary to use actuators and sensors on both sides of the bridge with one system slaved to the other.

Detailed design considerations

- **Performance considerations**
  - **Running parallelism, repeatability, and resolution.**
  - **Lateral and moment load support capability.**
  - **Allowance for thermal growth.**
  - **Alignment requirements.**
  - **Preload and frictional properties.**
- **Try to visualize forces and moments as "fluids" and see how they flow from the carriage to the bearing to the machine.**
- **For machine tool applications where high cutting forces and moments must be resisted:**
  - **One is virtually required to use an over constrained bearing arrangement.**
  - **With reasonable manufacturing tolerances, increased stiffness and elastic averaging effect can be beneficial:**



- **It is the wise design engineer that selects two possible options:**
    - **Do preliminary tests to determine which bearing is best.**
- **One should also consider:**
    - **Does the manufacturer offer a usable bearing from stock?**
    - **How long would a custom order take to be delivered?**
    - **How does the use of an available stock bearing affect the rest of the design?**
    - **Is friendly intelligent design assistance offered?**
    - **Has the manufacturer supplied bearings for a similar application before?**
- **What are the prototype and production quantity costs?**

Speed and acceleration limits

- < 60-120 m/min (2000-4000 ipm) and 1 g.
- At higher speeds, rapidly use up L_{100} life, and requires oil lubrication.

Applied loads

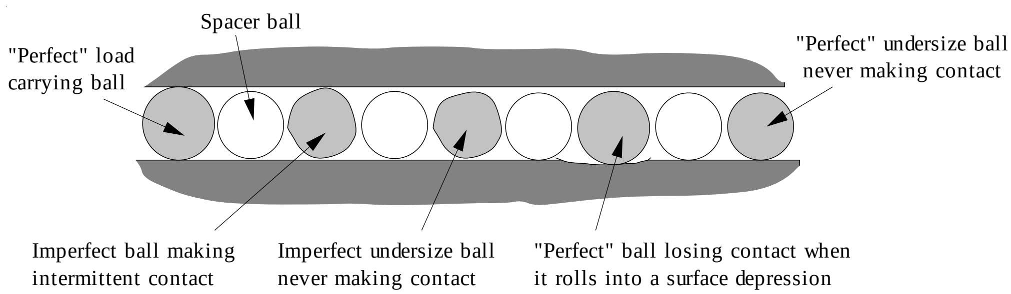
- Large load capacity is achieved with many elements.
  - Remember, load capacity quoted in a catalog is usually for 100 km of travel.
  - The load/life relation is cubic:

$$F_{atdesiredtravel} = F_{100\,kmratedload}\left(\frac{L_{de\sin km}}{100_{km}}\right)^{-1/3}$$

  - At 1000 km, the load capacity is $0.46F_{100\ km}$!
- For modular bearings, design data is available from manufacturers.
- Sensitive to crashes.
- For custom designed bearings, Hertz contact stress theory can be used.
  - Hertz contact stress theory is readily implemented in spreadsheet form.
  - All rollers are not preloaded evenly and many more rollers than theoretically required may be needed.

Accuracy

- **Axial: 1-5 microns depending on the servo system.**
    - **Specially finished systems can have sub-micron accuracy.**
- **Lateral (straightness) : 0.5 - 10 microns depending on the rails and rolling elements.**
- **Rolling elements are not necessarily round and of the same size:**



- **Look for noise spikes at D_{ball}, πD_{ball}, and $2\pi D_{ball}$**

- **Elastic averaging helps to reduce high frequency straightness errors, but they still exist.**
    - **Entrance and exit path profiles for recirculating elements greatly affect smoothness.**
    - **Spacer balls reduce skidding, but decrease load capacity and increase price, so they are very rarely used.**

- **THK's new retainer system virtually eliminate ball rubbing noise:**

■ Data concerning noise levels

Figure 5 compares the data concerning noise levels between the SSR and conventional type LM guide. The variable condition for noise comparison is the speed in meter per minute. These graphs show that the type SSR generates lower noise compared to that of the conventional type.

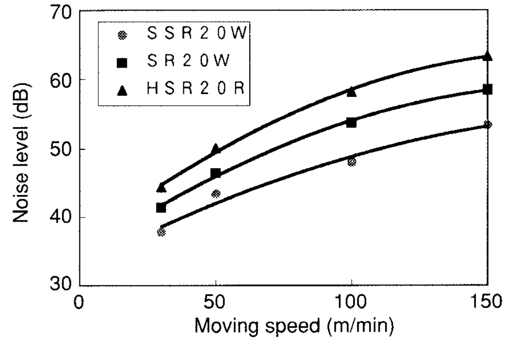


Figure 5 Comparison of the noise levels with respect to the LM guides' speed (m/min)

■ Data concerning rolling resistance

Fluctuation of rolling resistance obviously shows up in vertical usage. Fig. 6 displays rolling resistance data of the conventional product and Fig. 7 displays the same for SSR25W. Type SSR shows very small fluctuation of rolling resistance even at the vertical application and provides stable, smooth movement compared to the conventional type.

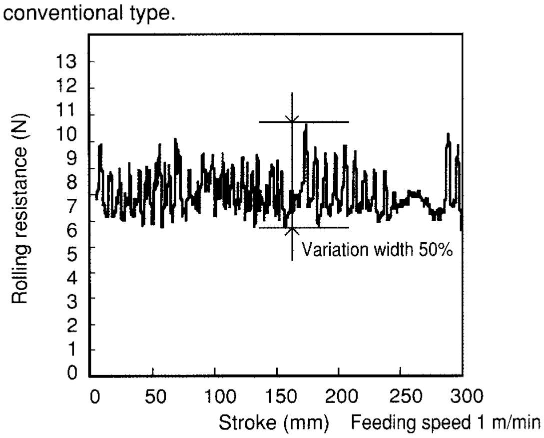


Figure 6 Rolling resistance in vertical direction (Conventional type)

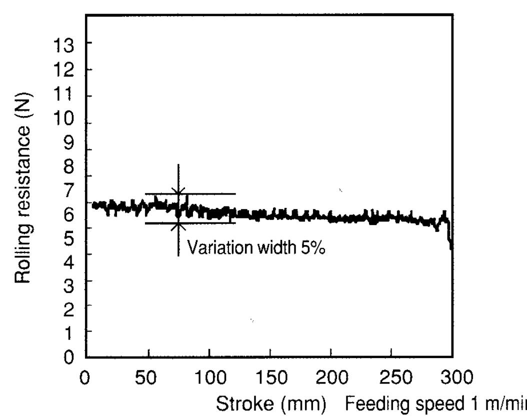
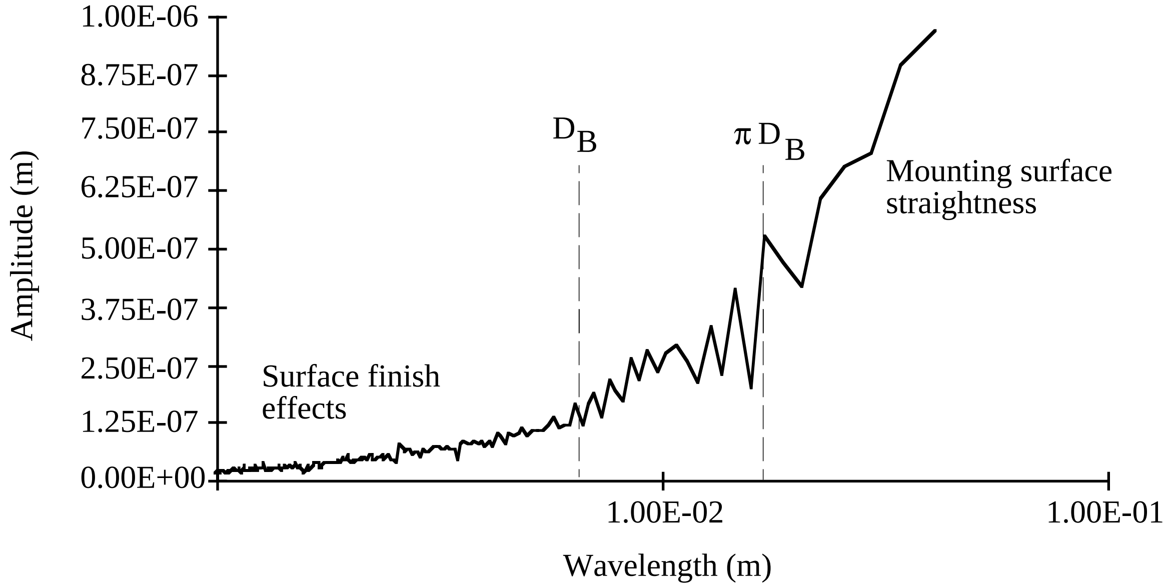


Figure 7 Rolling resistance in vertical direction (SSR25W)

- **Fourier transform of a linear guide's straightness errors:**



- **Note the small peaks in the vicinity of the ball diameter and circumference.**
  - **This is a good linear bearing.**
  - **The errors are dominated by the profile of the structure to which it is mounted.**
- **Lobes on balls and chatter on ground surfaces also contribute to the error.**
- **Longer wavelengths reflect the overall straightness.**

- **The FFT is one of the most powerful diagnostic tools at your disposal!**

THK developed a flexible molded plastic retainer that separate and lubricates the balls:

SSR
SILENT & SMOOTH

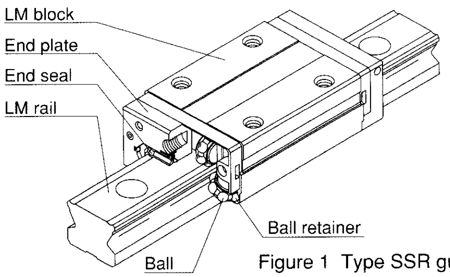


Figure 1 Type SSR guide structural drawing

The ball retainer eliminates friction between adjacent balls, thus extending the life of the grease and providing for maintenance free, low noise, comfortable sound guides with long lives. The high speed capability is also improved.

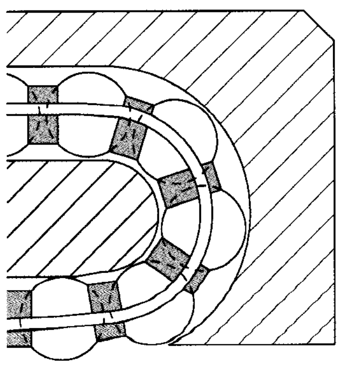
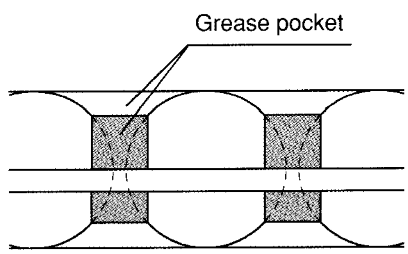


Figure 2 Ball circulating section



The grease circulates with the aid of the retainer.

Figure 3 Grease pocket

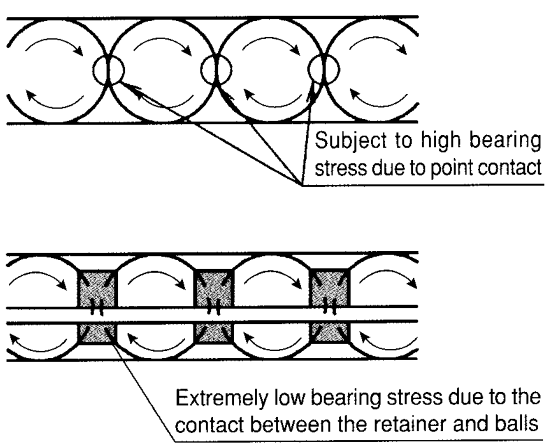


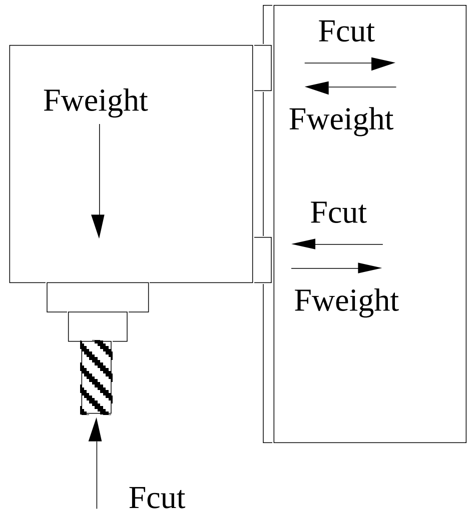
Figure 4 Friction

Preload

- **Prevents *lost motion* upon load reversal.**
- **If an 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.**
- **Preloads for different applications of recirculating ball modular linear bearings** (Courtesy of NSK Corp.)**:**

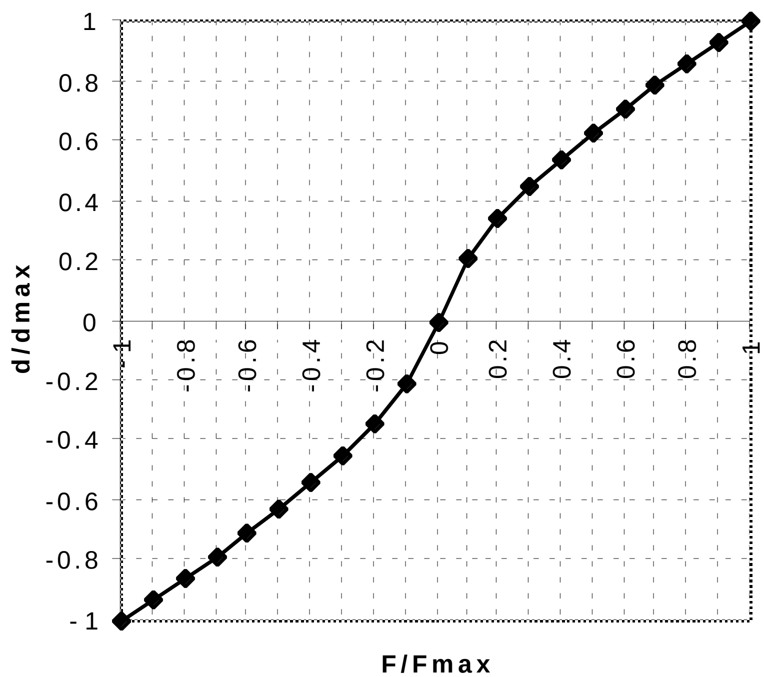
Preload	Characteristics	Operating conditions	Applications
Heavy	Large Hertz contact area, greater friction and damping	Resists vibration and shock. Withstands cantilevered loads and heavy cutting forces	Machining centers, turning centers
Medium	Modest Hertz contact area and damping, less friction	Withstands light vibration and shock and caantilevered loads. better for igher speeds	Grinding machines, higher speed machining centers
Light	Small Hertz contact area minimizes friction while maintaining ball spacing to minimize friction	No cantilevered loads. Light and precise operation	Coordinate measring machines, high speed machines, EDM machines
Very light-clearance	No defined contact footprint	Machines with large amounts of thermal growth, minimal cost	Welding machines, automatic tool changers, material handling equipment

- **Be careful when the bearing goes through alternating tension and compression.**



- **When the cantilevered load unpreloads a bearing, an impact load could reverse the load and damage the bearing.**

- **Stiffness is proportional to F2/3, so when the load reverses, there will be a change in stiffness.**



Stiffness

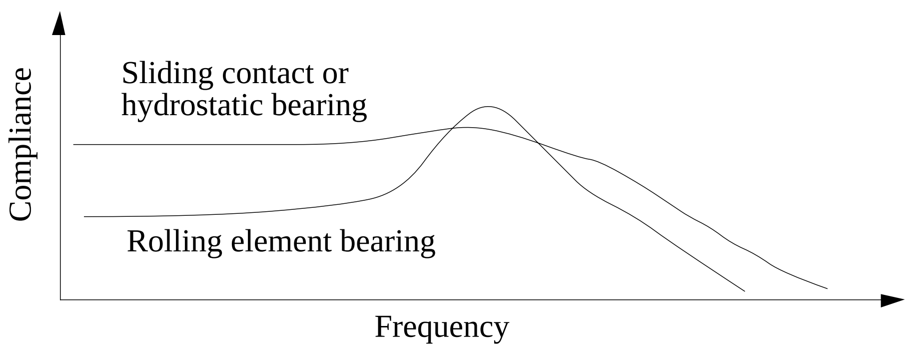
- **Can be made equal to that of the rest the machine.**
- **Nonlinear (Hertzian), so preload is important.**

Vibration and shock resistance

- **Poor to moderate.**
- **Significant motion is required periodically to reform a hydrodynamic lubrication layer to prevent fretting.**

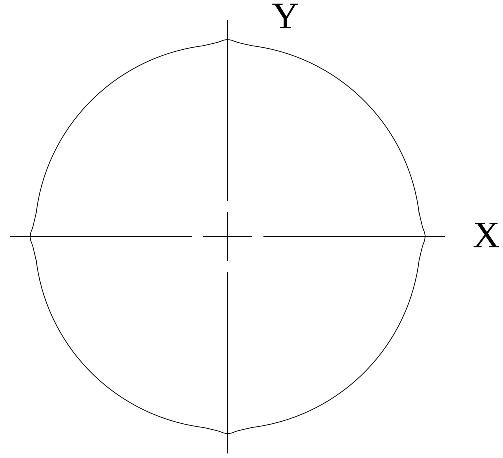
Damping

- **Additional damping is obtained from the lubrication layer; however the squeeze film area is very small.**
- **Along the direction of motion, damping is negligible.**
- **Non-load carrying sliding contact bearings are sometimes added where damping is very important (e.g., grinders).**



Friction

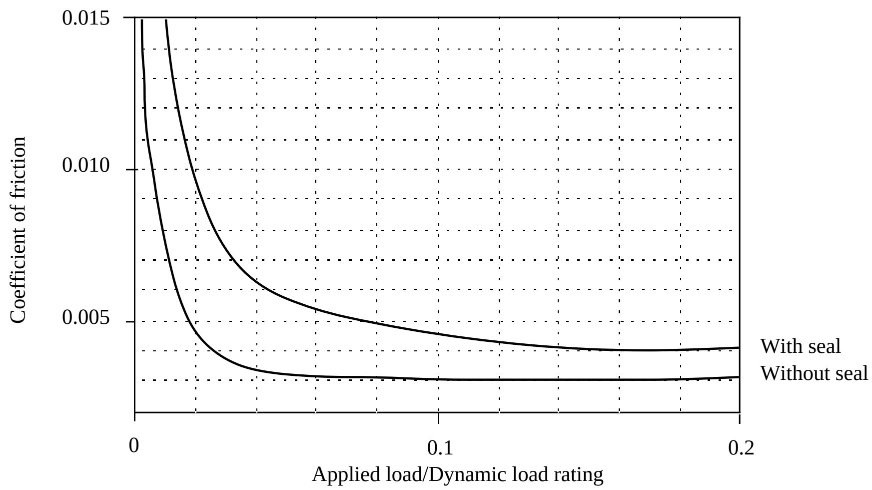
- **Static friction approximately equals dynamic friction at low speeds, so stick slip is often minimized.**
- **For heavily loaded tables, static friction is still significantly greater than dynamic friction.**
  - **Errors will appear at velocity crossovers:**



Bearing	**"Dimple" size**
Sliding contact	**10-20 μm**
Recirculating rolling element	**3-5 μm**
Crossed rollers	**1-2 μm**
Hydrostatic or aerostatic	**0 μm**

- **Linear encoder allows the I term in a PID controller to increase as the ballscrew winds up.**
- **Rotary encoder senses twist of the ballscrew and acts to effectively decrease the I term gain at zero velocity.**
- **The effect can be overcome with gain scheduling:**
  - **The controller decreases the integrator gain at zero velocity.**

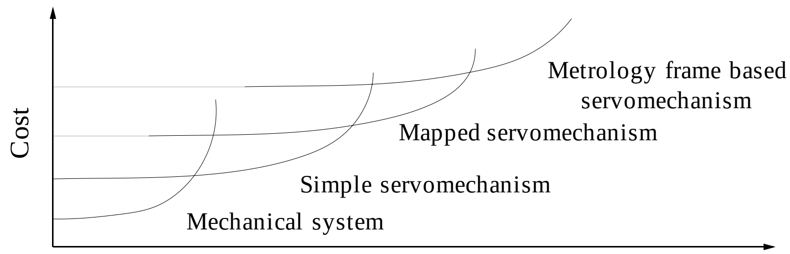
- **Finite contact area means true rolling motion is not obtained:**
  - **Thus there will always be some slippage and friction (differential contact diameter slip).**
- **Effect of applied load on friction coefficient μ of a recirculating ball, circular arc groove linear motion guide** (Courtesy of THK Co., LTD.)**:**



- **It is important to use cover plugs on linear guide rail bolt holes.**
- **Seals passing over open holes produce varying friction loads, and can let dirt get into the bearings.**

Thermal performance

- **Finite friction coefficient generates heat.**
- **Small contact area does not transmits heat well.**
- **Modular bearings themselves may be thermally stable:**
    - **But can heat from a component (e.g., a spindle) expand the structure and overload the bearings?**
- **Above 1 m/s, one may want to switch to hydrostatic or aerostatic bearings:**



$$\text{Difficulty} = \frac{\text{Environment} \times \text{Load} \times \text{Range} \times \text{Speed}}{\text{Accuracy}}$$

Environmental sensitivity

- **Generally intolerant of foreign matter**
- **Wiper seals are sufficient for low accuracy applications.**
- **For high accuracy applications, bearings should be protected with wipers and/or way covers.**

Support equipment

- **Many units are sealed for life.**
- **Some units require a periodic application of grease.**
- **For very high cycles (as on a high speed machining center, an oil lubricator should be installed.**
- **Where does the oil go?**
  - **Design in oil collection gutters into the machine casting.,**
  - **This will also facilitate the use of modular hydrostatic bearings (HydroRail™ bearings) that are bolt-for-bolt compatible with rolling element profile rail bearings.**

Aesop's[1] Surface Self Compensated Profile Rail Linear Hydrostatic Bearing System: The HydroRail™

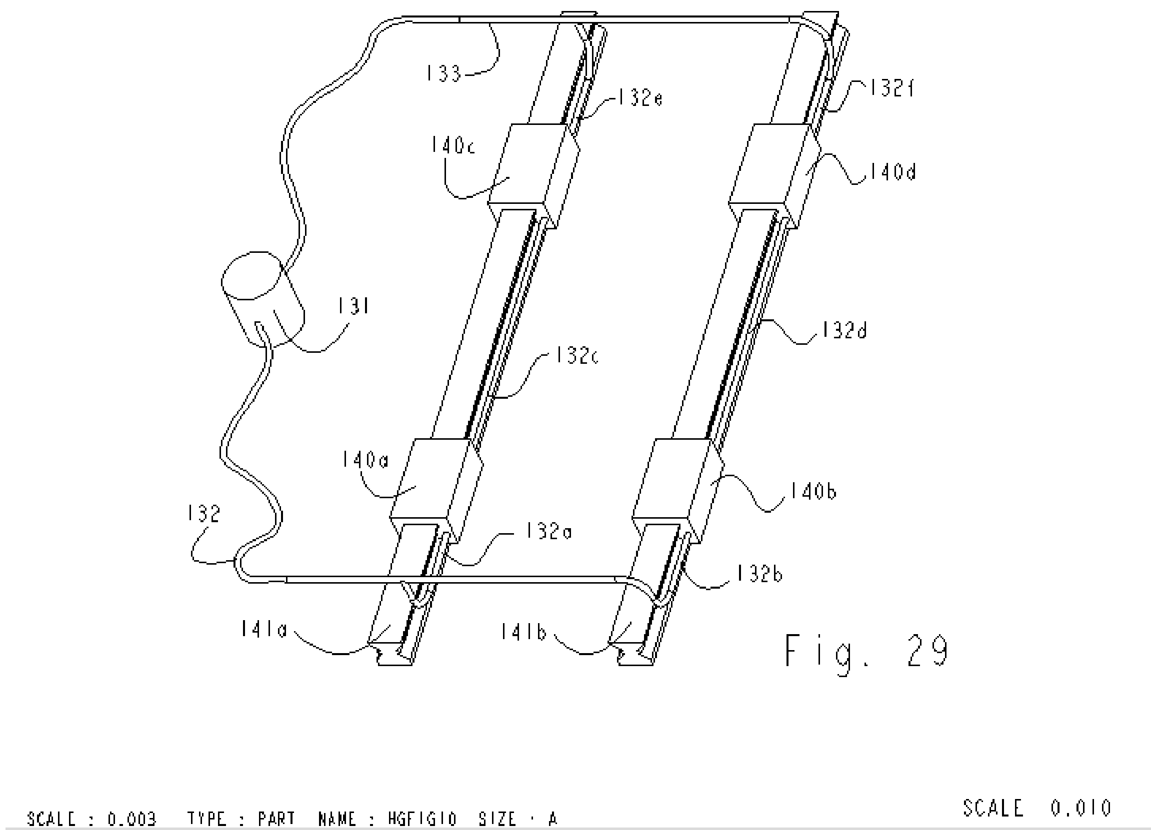


Fig. 29

[1] Patents pending. Aesop, Inc. PO Box 2126, Concord, NH 03302-2126, Fax 603-224-5369

Rolling element life

- **The basic dynamic load, C_N, is the load under which 90% of a group of bearings will support while traveling a distance of 100 km.**
- **For an applied load F_C, the load-life relation for rolling balls is typically**

$$L\ (\text{km}) = 100 \left(\frac{C_N}{f_w\, F_C}\right)^3$$

For rolling cylinders the load-life relation is typically

$$L\ (\text{km}) = 100 \left(\frac{C_N}{f_w\, F_C}\right)^{10/3}$$

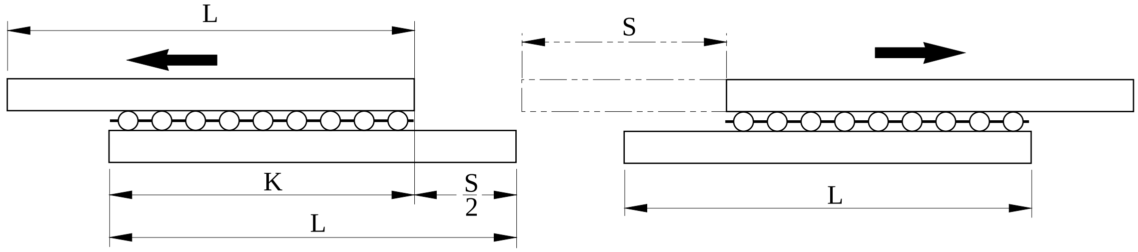
The service factor f_W depends on the type of operating conditions:

f_W = 1.0-1.5 for smooth operation with no impact or vibration loads (e.g., semiconductor equipment).
f_W = 1.5-2.0 for normal operation (e.g., CMMs).
f_W = 2.0-3.5+ for operation with impact or vibration loads (e.g., machine tools).

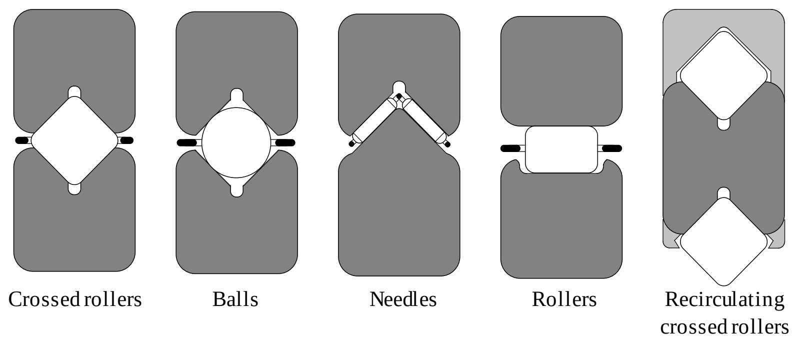
For very severe load and vibration situations, such as creep feed grinders, f_W may be as high as 10.

Non-recirculating crossed roller bearings

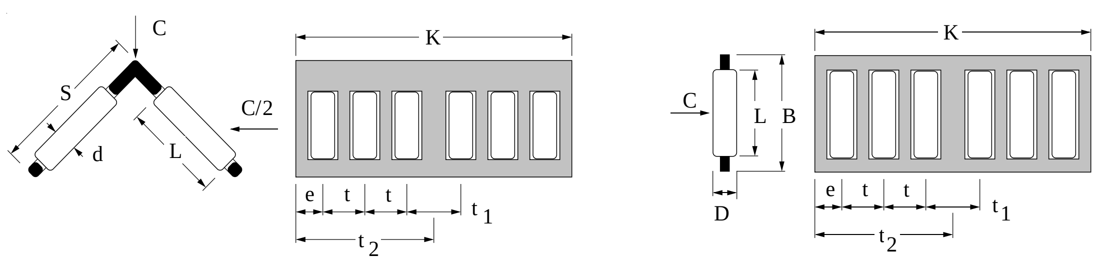
- **Quiet, inexpensive, versatile bearing for short travel.**
- **Rollers travel half the distance of the moving member:**



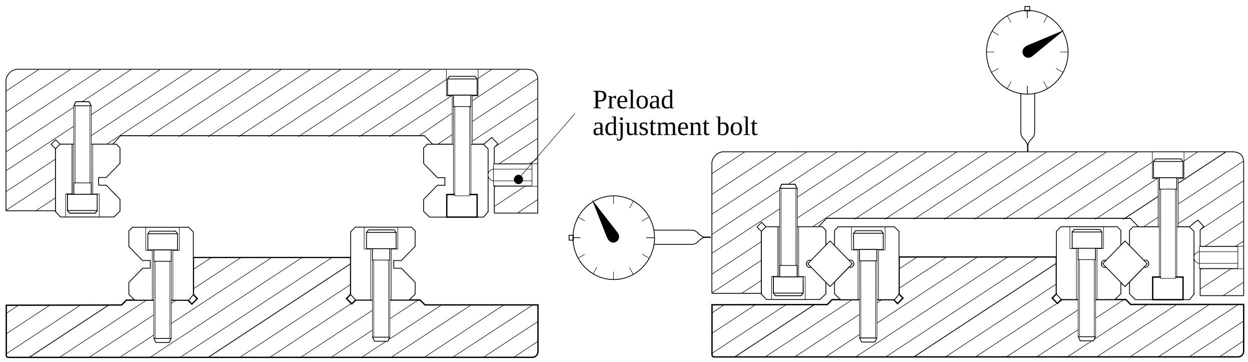
- **There are many variations on this design:**



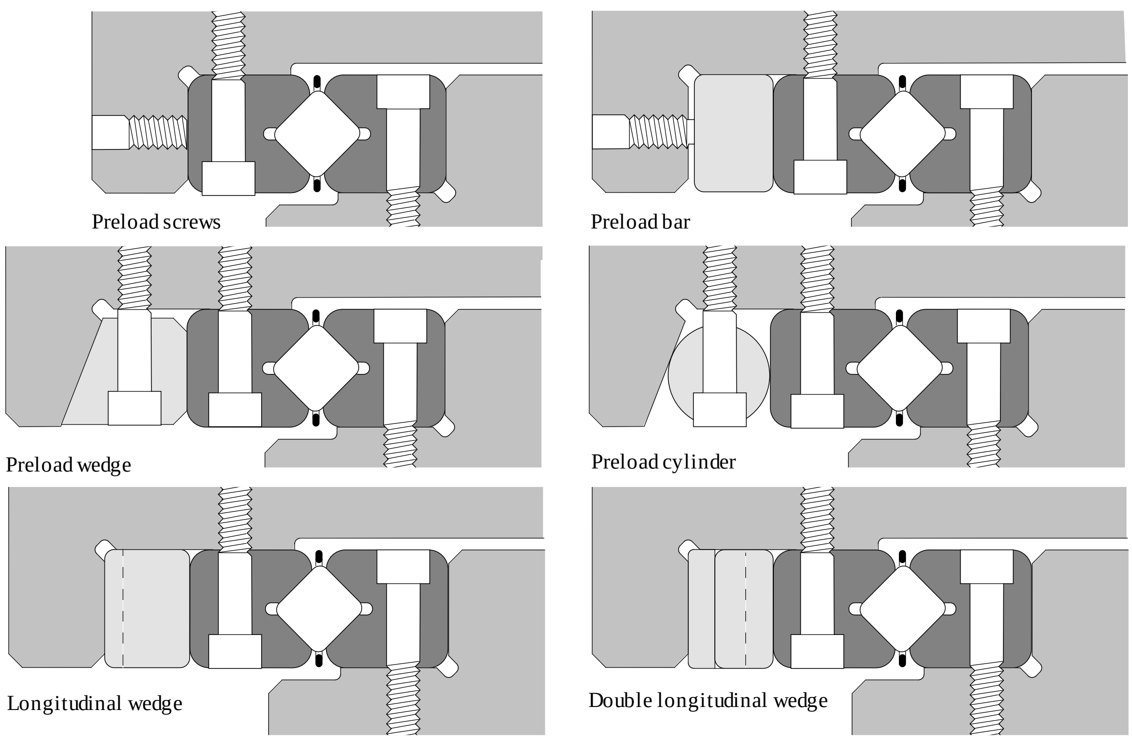
- **There are many other variations of non-recirculating linear motion roller bearings.**
- **Typically available modular nonrecirculating roller linear bearings** (Courtesy of Schneeberger Inc.)**:**



- **Typical assembly of crossed roller supported slide:**

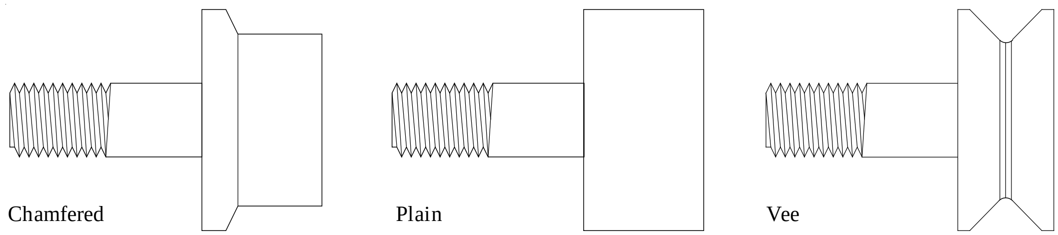


- **Methods for preloading crossed roller bearings:**



Wheels on rails

- **An inexpensive means of obtaining modest performance for a very low cost is to use wheels (cam followers) on rails:**



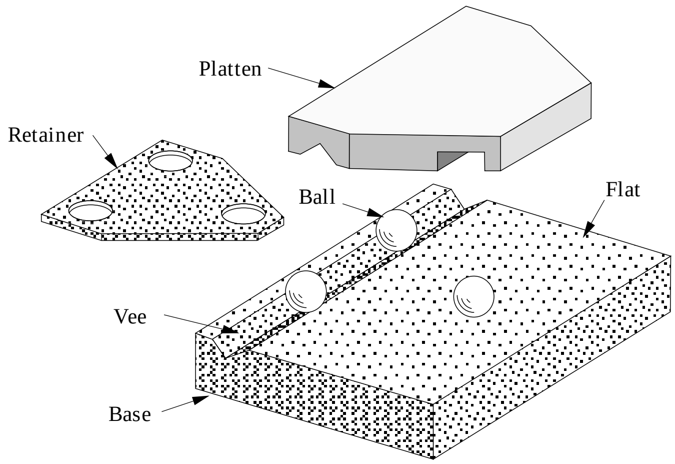
- **Kinematic configurations of instrument ball bearings on polished ceramic rails can yield sub-micron performance for a very low cost.**

- **Beware of the formation of frictional polymers on dry-running systems.**

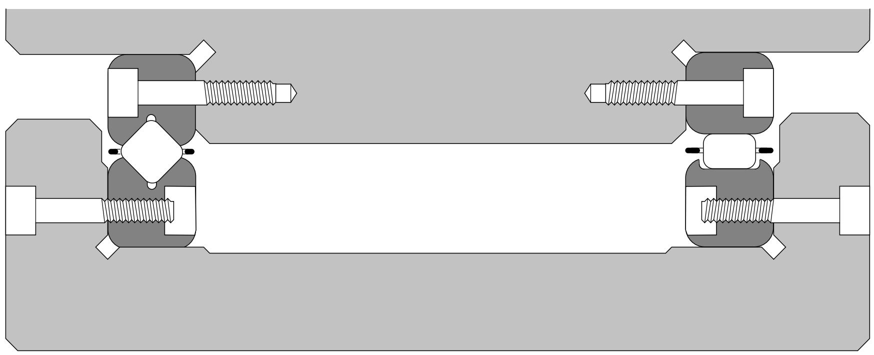
    - **As elements roll, they compress organic molecules in the air onto the surface and build up a layer.**

    - **This layer is not uniform and causes a bumpy ride and velocity control problems.**

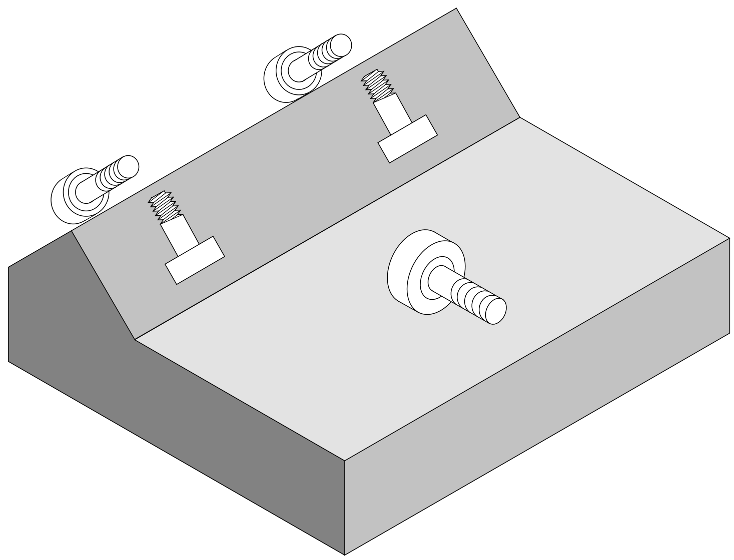
- **Kinematic designs are often used:**



- **Quasi-kinematic arrangement of crossed roller bearings and rollers on flat rails:**



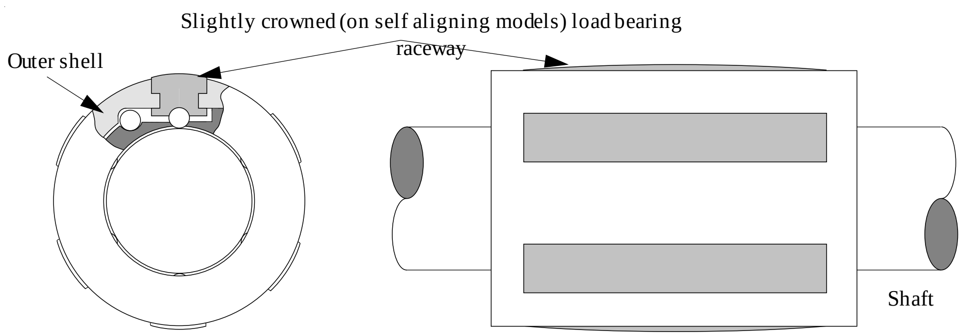
- **Concept for a cam-roller based kinematic design (crowned rollers must be used if slip-noise is to be avoided).**



- **Many other variations are possible, such as rollers on round rails.**

Ball Bushing™ bearings

- **Invented in the 1950s by John Thomson.**
- **A linear bearing which incorporates recirculating balls on a round shaft (e.g., a Ball Bushing™ bearing)** (Courtesy of Thomson Industries.)**:**



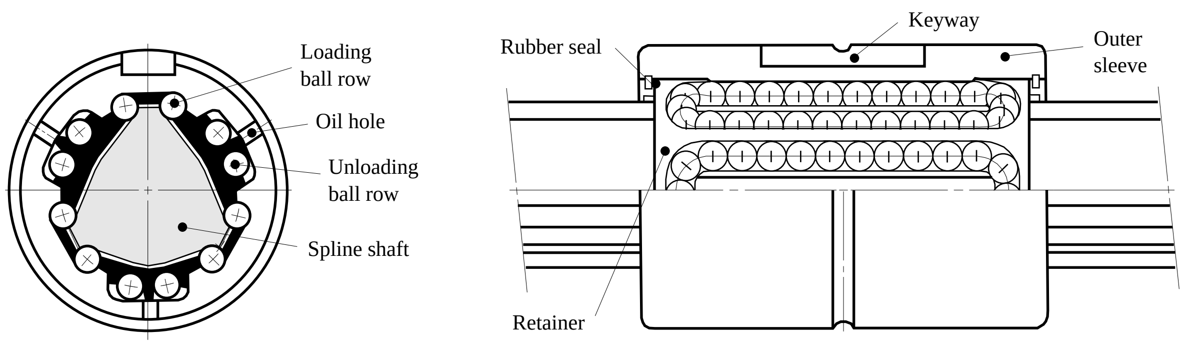
- **Round shafts are inexpensive to grind or hone.**
- **Easy to design and manufacture machines using Ball Bushing™ bearings.**
- **Rotary and torque transmitting designs are available.**
- **Generally intended as a modest accuracy bearing (material handling devices), counterweight guides).**
- **Ball/shaft interface is not optimal for load capacity or stiffness.**
  - **Early machine tools found that by overloading the preload, circular arch grooves cold formed in the shaft.**
  - **Replace the balls and the bearing would be reassembled to perform at higher loads and have greater stiffness.**
  - **This in effect acted as the forerunner of profile rail bearings (linear guides).**
- **Instrument grades are often used to guide the shafts in gage heads (e.g., an LVDT probe).**

- **Flexures can be used to allow for rail misalignment while allowing a system to be preloaded:**

- **Constant preload is supplied via disc spring washers even if there are variations in rail size.**
- **The flexure connection to the outrigger bearing prevents rail parallelism errors from affecting running friction.**
- **Aluminum extrusions are not too expensive.**
    - **Like the figure above, it is often economical to design a shape with the grooves for the bearing rails to rest in.**

Ball splines

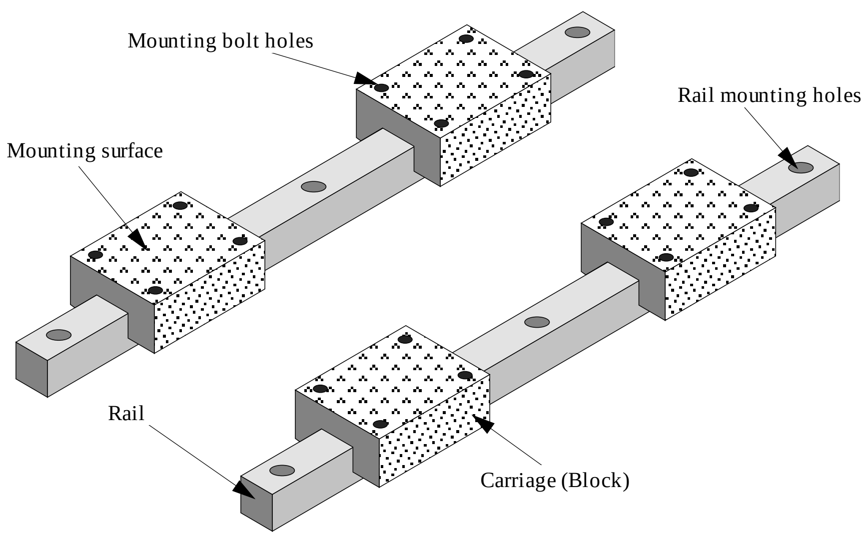
- **A linear ball bearing on a shaft with circular arch groove spline.**
    - **Has increased load capacity and torque transmission capabilities.**
- **Construction of a ball spline for supporting radial and torsional loads** (Courtesy of THK Co., LTD.)**:**



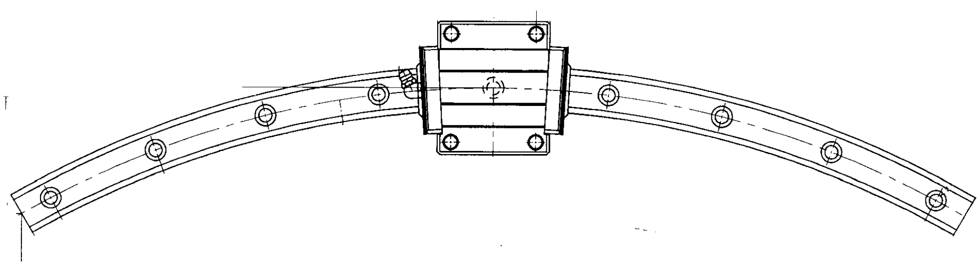
- **The ball spline followed the Ball Bushing.**
- **It was then mounted o a support along its length.**
- **When the support was made integral with the ball spline, the linear guide was born.**

Profile rail linear bearings (Linear motion guides)

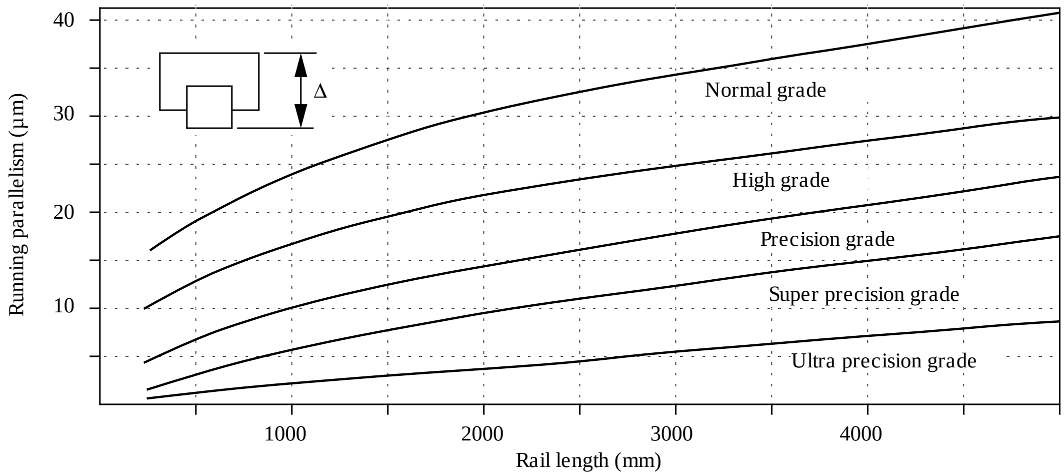
- **With modern grinding techniques, grooved rails can be made very accurate.**
- **Ball/groove interface can be optimized for maximum load capacity and stiffness, or minimum friction.**
- **Easy to design and manufacture machines using linear motion guides.**
- **Analysis of linear guided systems is easily executed using spreadsheets.**
- **Basic components of a linear motion guide bearing system:**



- **Specialized Linear Guides are available for curved paths, and also with integral gear racks for long range of motion machines (from THK Corp.)**



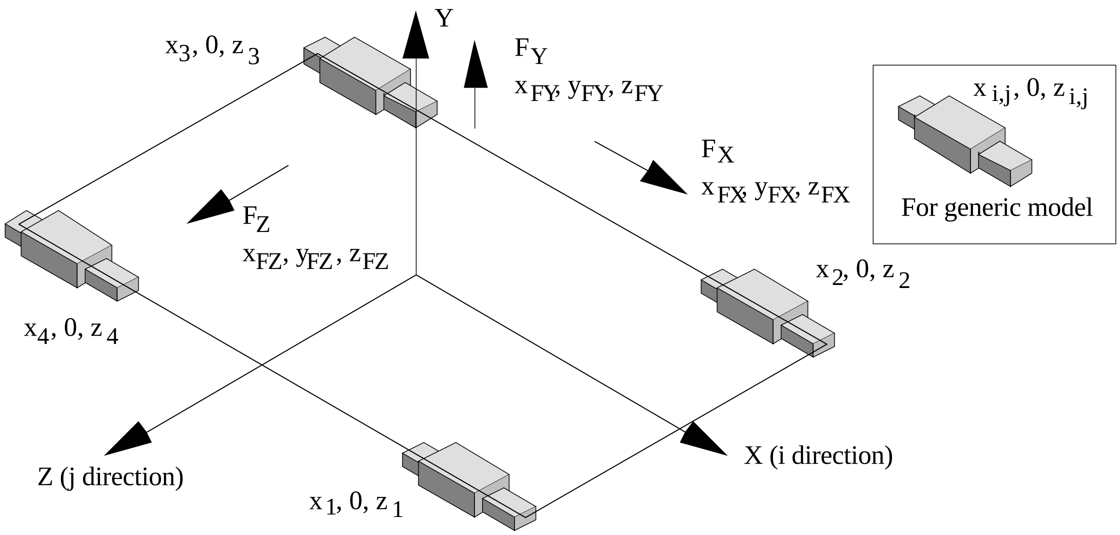
- **Typical running parallelism of linear guides:**



- **The price ratio of Normal grade and Ultra Precision grade is typically 1:2.**

Load calculations for linear motion guides

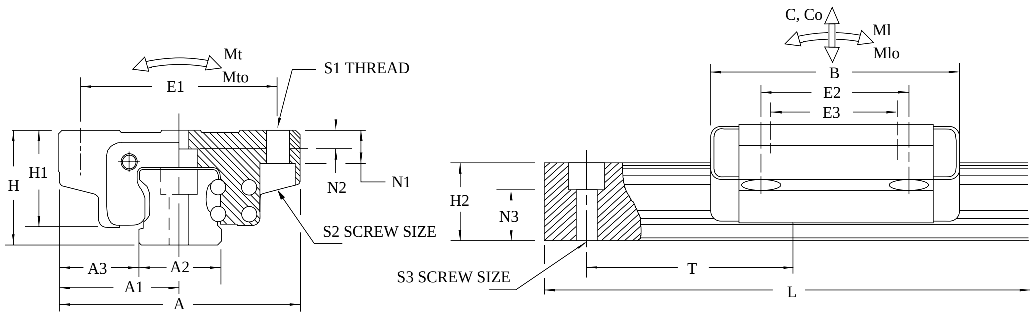
- **Generic form once implemented on a spreadsheet is the easiest to use.**



- **Even though the system is over constrained, reasonable assumptions can be made.**
- **The structure of the carriage must be designed so that its deformations are within those allotted by the error budget.**
- **Thus for the purposes of finding approximate bearing reaction forces:**
  - **Assume that the carriage and structure the rails are mounted to behave like a rigid body.**
- **Forces can act in any direction at any location.**
- **Moment stiffness of the bearings is insignificant.**
- **Forces are distributed in relation to the bearings' proximity to them.**
- **See the text for the equations for force distribution.**

Load capacity and stiffness of linear motion guides

- **Back-to-back circular arch linear guides allow a single rail to have high moment capacity** (Courtesy of Thomson Industries.)**:**

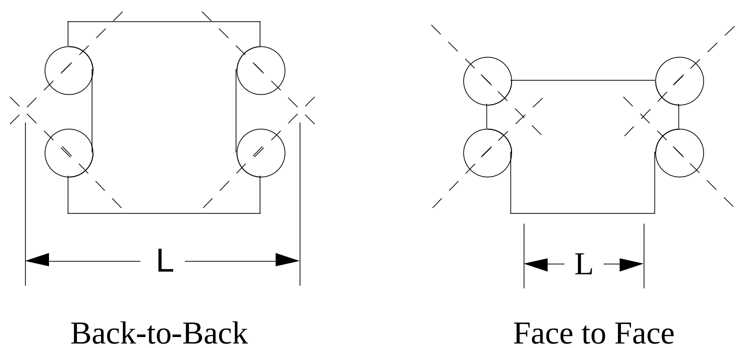


Model*	A	A1	A2	A3	H	H1	H2	B	E1	E2	E3	E3 (Alt)	N1	N2	N3	T	S1, S2, S3
ACG-25	70	35	23	23.5	36	29.5	24.5	81	57	45	40	45	9.0	4.5	16.0	60.0	M8,M6,M6
ACG-35	100	50	34	33.0	48	40.0	32.0	106	82	62	52	62	12.0	7.0	21.0	80.0	M10,M8,M8
ACG-45	120	60	45	37.5	60	50.0	40.0	135	100	80	60	80	15.0	8.0	24.0	105.0	M12,M10,M12

* Maximum rail length is 3000 mm.

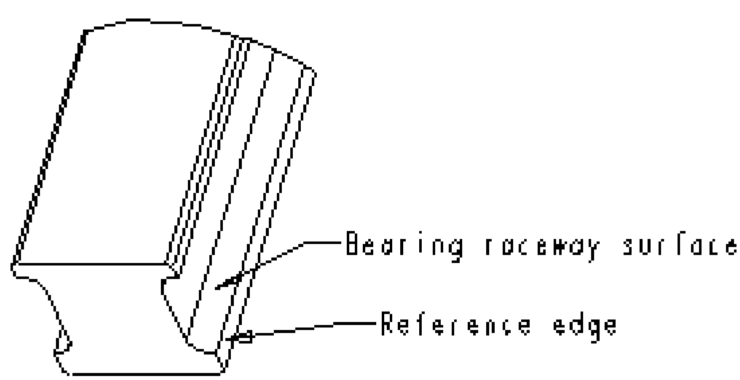
Model	Load Capicity (N)		Moment Capacity			
	C	Co	Mt	Mto	Ml	Mlo
ACG-25	13500	25000	190	350	95	175
ACG-35	25500	44000	530	910	265	455
ACG-45	42500	70500	1160	1910	580	905

- **When comparing the load capacity of different bearings:**
  - **Be careful of which type of load-life the manufacturer defines:**
    - **L10 life at 50 km, 100 km, 500 km, 1000 km etc.?**
    - **A bearing optimized for long life may have a lower load rating at a shorter travel life.**
- **When moment capacity is required, such as when using a single rail:**
  - **Use a very wide rail, or**
  - **Use a back-to-back bearing configuration**

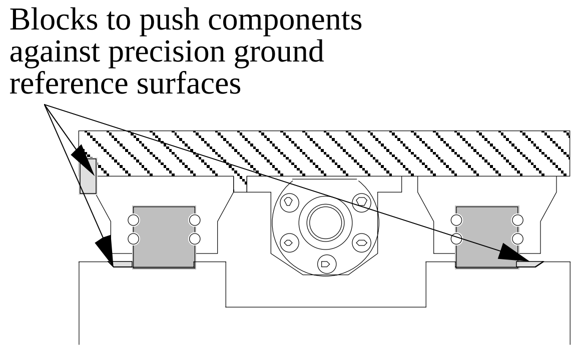


Linear guide rail mounting

- **When manufactured, ideally the races and reference edges of the rails are ground simultaneoulsy and are parallel.**
    - **This ensures that the races are parallel to the reference edges.**
    - **On lower grade linear guides, spindle error motions and grinding wheel dressing errors can cause non-parallelism.**
- **Higher grade linear guides are selected so the parallelism is very good.**
- **When the rail was removed from the grinder after manufacturing, the rail will not be perfectly straight**
    - **Caused by grinding of a non-uniform hard martensite layer.**
    - **Therefore linear guide depends on a flat surface and a reference edge for straightness.**

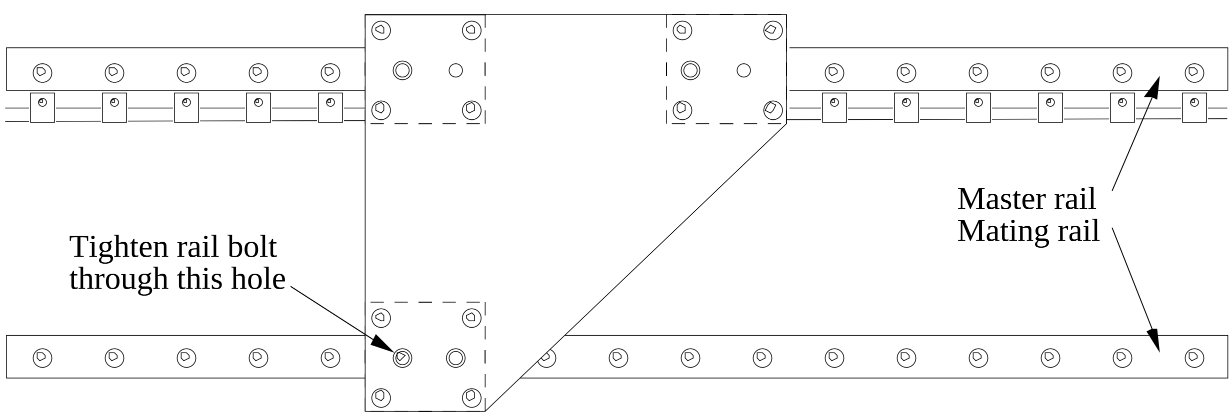


- **For the highest grade linear guides, one can use *hard mounting*.**
  - **Force both rails against parallel reference edges using clamping blocks.**



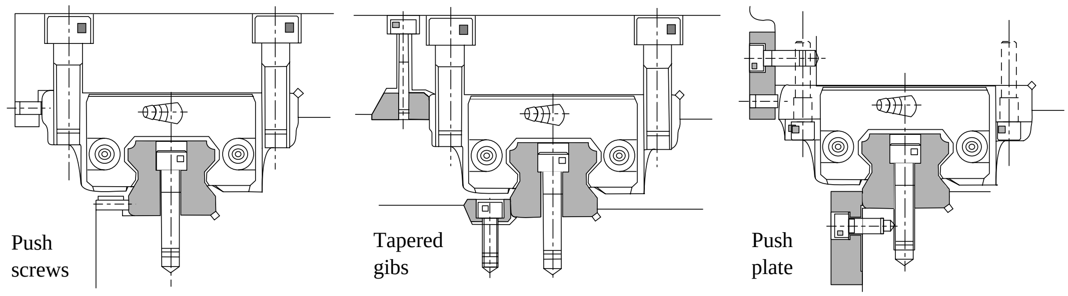
- **Pros:**
  - **High rigidity for applications with high side loads.**
  - **Less chance for human error.**
- **Cons:**
  - **Forcing the rails against parallel reference edges can overload the balls in the carriages.**
    - **The carriages want to follow the non-straight races.**
    - **The Hertz stress rises rapidly when geometric congruence is forced.**
      - **This occurs more often when using normal grade linear guides (e.g., those used in material handling systems):**

- **A more tolerant mounting method uses a Master rail and a mating rail.**
  - **A master rail is bolted down against a reference edge.**
  - **The mating rail is lossely bolted down (hand tightened bolts).**
  - **A fixture with two carriages on the master rail, and one carriage on the mating rail is moved from one end of the stroke to the other end.**
  - **The mating rail bolts are tightened through a hole in the carriage center as the fixture moves down the rails.**
  - **This forces the races of the mating rail to be parallel to the master rail.**



- **Pros:**
  - **Mounting-induced Hertz stresses are minimized.**
  - **Only one reference edge has to be machined.**
- **Cons:**
  - **A special fixture is required, but it can be the machine carriage.**
  - **Epoxy may be used to pot the mating rail's edges in place to better resist side loads.**

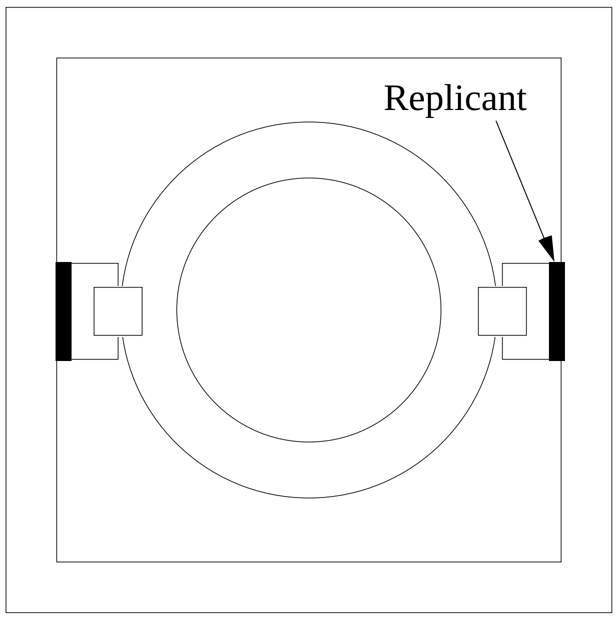
- **Linear guide carriage mounting methods** (Courtesy of THK Co., LTD.)**:**



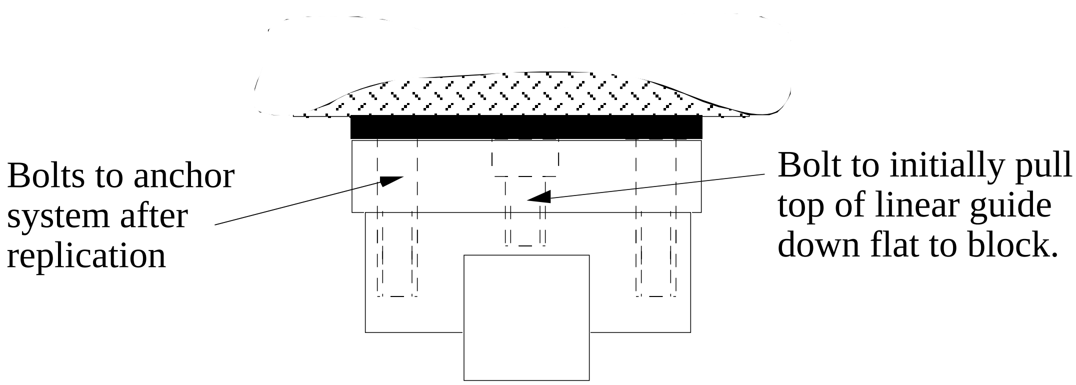
- **The mounting surface's surface finish is not too critical, except to optimize joint stiffness.**
- **A milled surface can be less costly than a ground surface.**
- **If the milling machine straightness is acceptable, the surface may not have to be ground.**
- **The rails and rolling elements create an averaging effect for short wavelength errors (e.g. surface finish).**
- **Generally, surface grinders can create a straighter surface than a milling machine.**

Replication

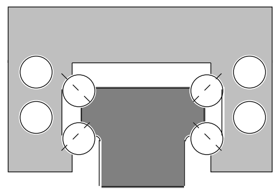
- **Replication can be used to ensure that bolting the linear guide carriage to the structure does not overload it.**
- **It can reduce cost by eliminating some machining.**
- **Example from a CNC waterjet machine, where the axes' carriages are cast, but only the outsides are machined:**



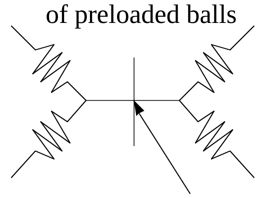
- **Preloaded precision linear guides depend on their top surfaces being bolted to a flat surface for proper preload.**
- **An intermediate "preload plate" can be used if needed:**

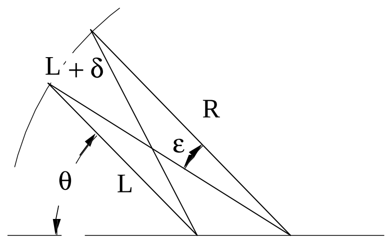


Why face-to-face linear guides have a large misalignment capability:



Face-to-face linear recirculating rolling element bearing





- **The bearing block rotates about an effective center:**
  - **When it is subject to an applied moment.**
  - **When geometric congruence is enforced.**
    - **When two parallel rails are not coplanar, so the tops of the bearing blocks are shifted in height.**
    - **When a component is bolted to the tops of the blocks, they are forced to rotate by a fixed amount ε.**
- **This is true for back-to-back or face-to-face arrangements of bearings.**

- **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:**

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

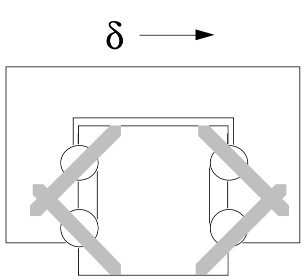
- **The displacements δ and θ are small, so with small angle approximations:**

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

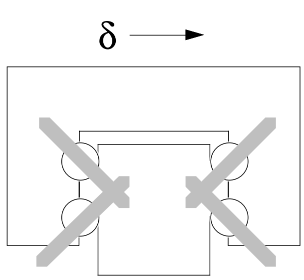
- **For a face-to-face arrangement of bearings, θ is acute ($\cos\theta$ is positive) and *a* is small.**
  - **Thus δ is small and $F = k\delta$, so F on balls is small.**
- **For a back-to-back arrangement, θ is obtuse ($\cos\theta$ is negative), and *a* is large.**
- **Thus for a fixed displacement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

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

- **Typically $\delta_{back\text{-}to\text{-}back} = 2\delta_{face\text{-}to\text{-}face}$**

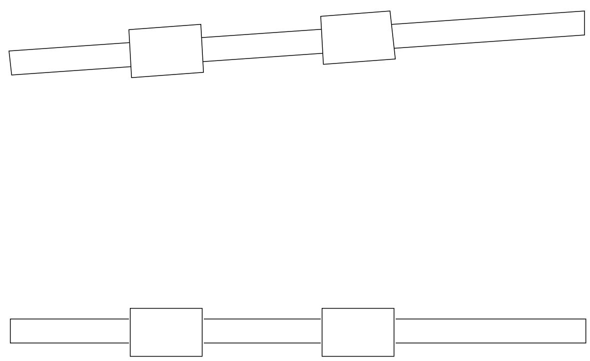


Back-to-Back

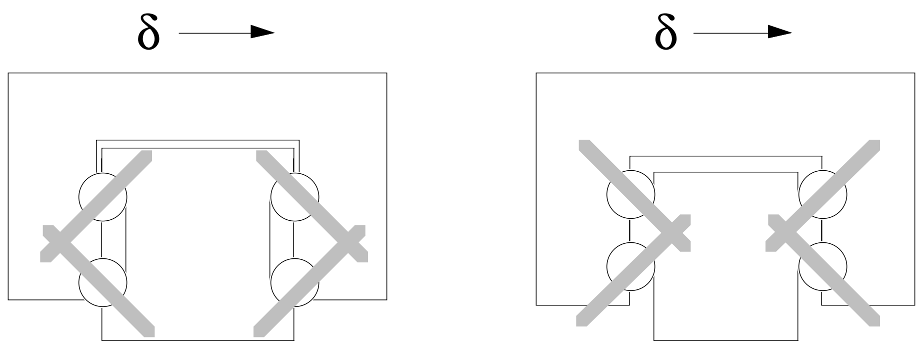


Face to Face

- **Force in a spring is proportional to the displacement.**
  - **Hence the face-to-face bearing is subject to lower stresses when it is angularly misaligned.**
  - **It will also have a lower moment capacity.**
  - **In the majority of cases, moment capacity is obtained by spacing two parallel rails far apart.**
- **If bearing blocks have parallelism errors, a face-to-face design will accomodate the angular orientation errors better.**
- **If rails have parallelism errors, the changing-center-distance error will cause the same stress level increases as in a back-to-back design.**



- **Hertz stresses caused by lateral displacement will be the same for back-to-back or face-to-face linear guides.**

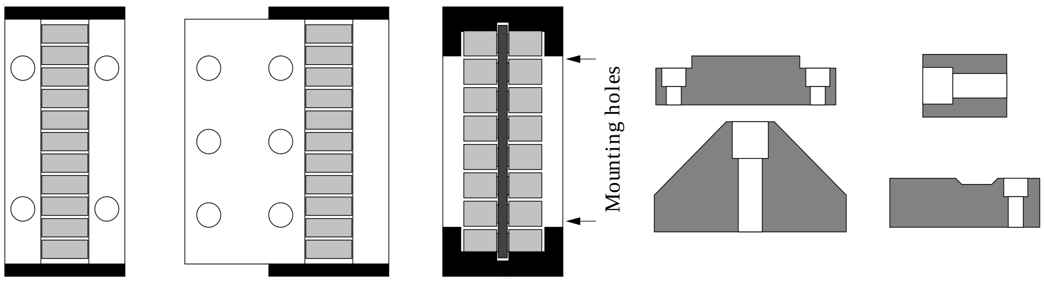


Back-to-Back

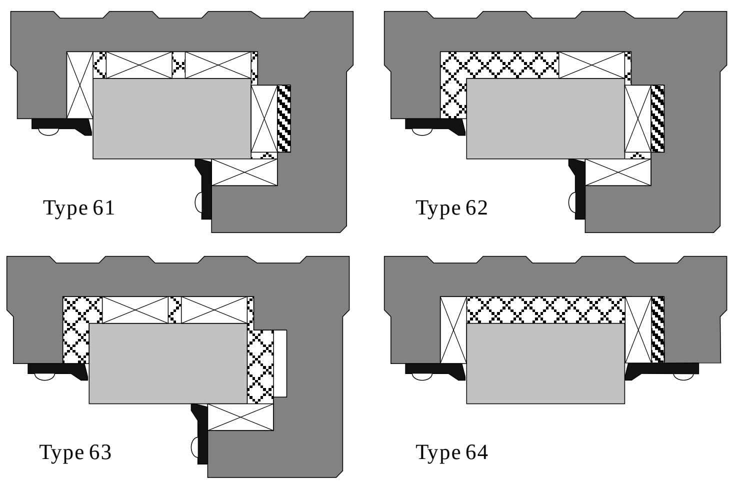
Face to Face

Recirculating rollers

- **Very high load capacity and stiffness, but alignment is critical.**
- **Crawler track type recirculating roller bearings for linear motion and some typically available rail types:**



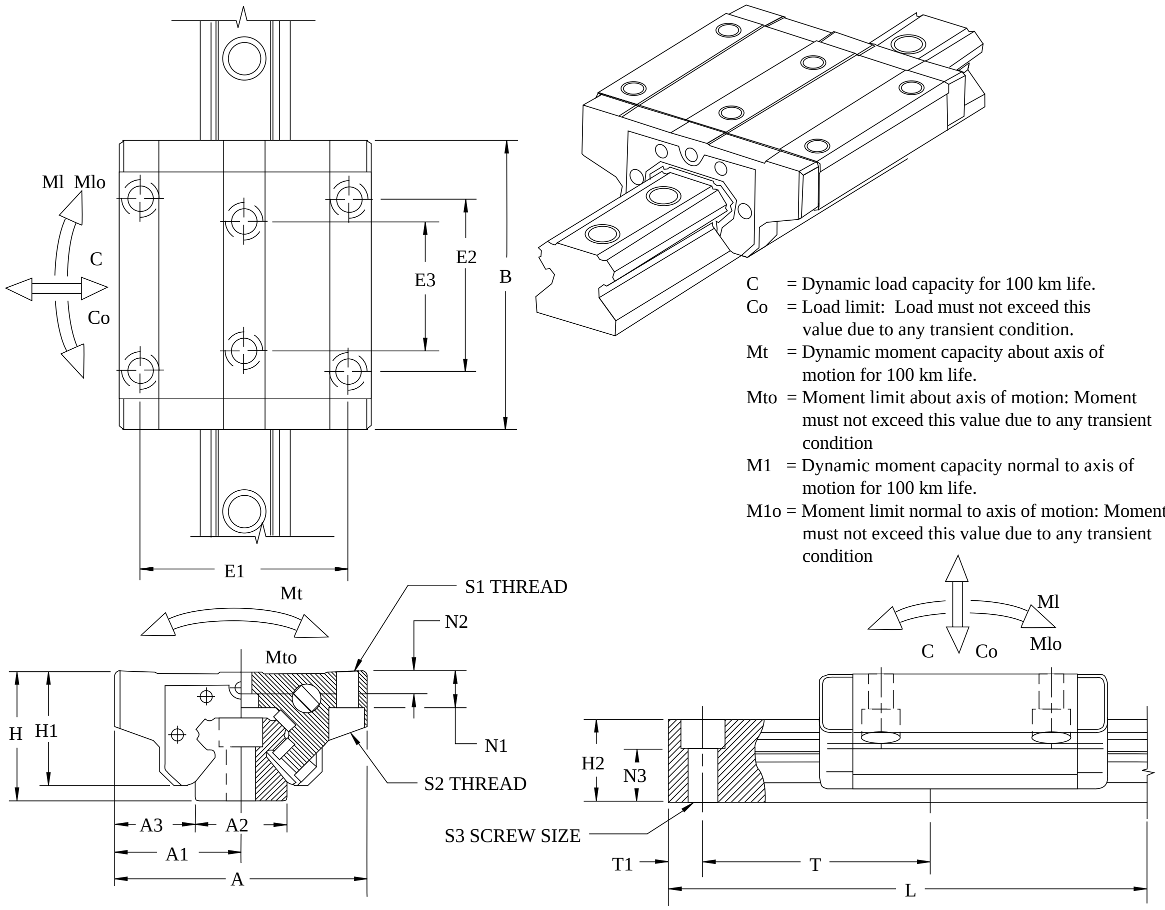
- **Sometimes called *roller packs*.**
- **Multiple crawler track tread type recirculating roller linear bearings for use on rectangular rails** (Courtesy of Schneeberger Inc.)**:**



Cylindrical recirculating rollers on crowned races

- **The obvious load carrying advantages of rollers over balls is somewhat tempered by:**
    - **Sensitivity to misalignment, skewing, and edge loading.**
    - **Effective line contact generally gives this type of bearing the highest load capacity, stiffness, and damping.**
- **These problems can be overcome with the use of cylindrical rollers on a continuously radiused race.**
    - **With modern CNC dressers, it is easier to grind a curved race accurate, than a barrel-shaped roller.**
- **In this design, the cylindrical rollers are loaded between two arcuate (curved) races:**
    - **When translated or rotated relative to each other, they still present the roller with large radii to roll upon.**
- **The bearing has characteristics similar to those of linear guide type bearings:**
    - **It has higher load capacities and stiffnesses.**
- **Because the bearing is so stiff, due to line contacts, and to maximize the benefits of the arcuate rail shape:**
    - **A face-to-face rail design is used.**

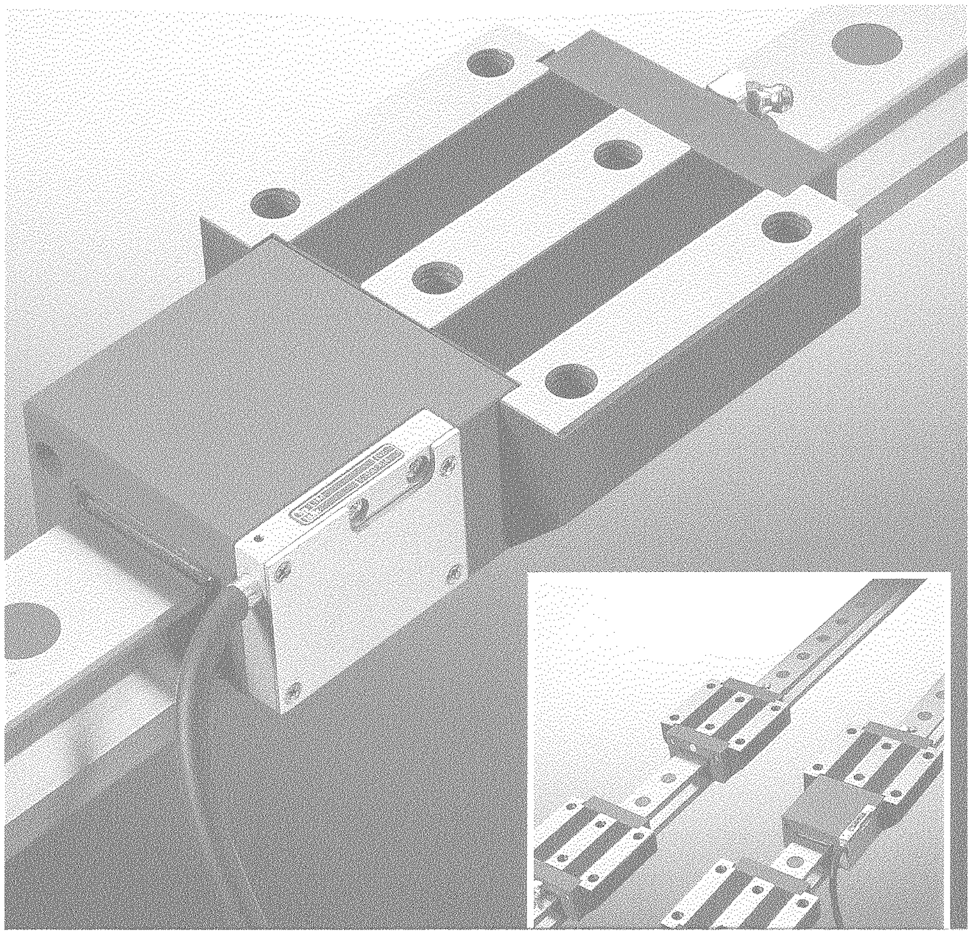
- **Accumax™ roller bearing** (Courtesy of Thomson Industries.)**:**



- **Rollers are so stiff, that the face-to-face design is very advantageous.**

Integrated linear bearing and sensor

- **Monorail bearing developed by Schneeburger to eliminate assembly & alignment issues associated with linear encoders:**



- **Magnetic scale is attached to the rail, and the read-head to the carriage.**
- **Recirculating rollers on flat surfaces on profile rails.**
- **Line contact generally gives this type of bearing the highest load capacity, stiffness, and damping.**

Aesop's[2] Surface Self Compensated Profile Rail Linear Hydrostatic Bearing System: The HydroRail™

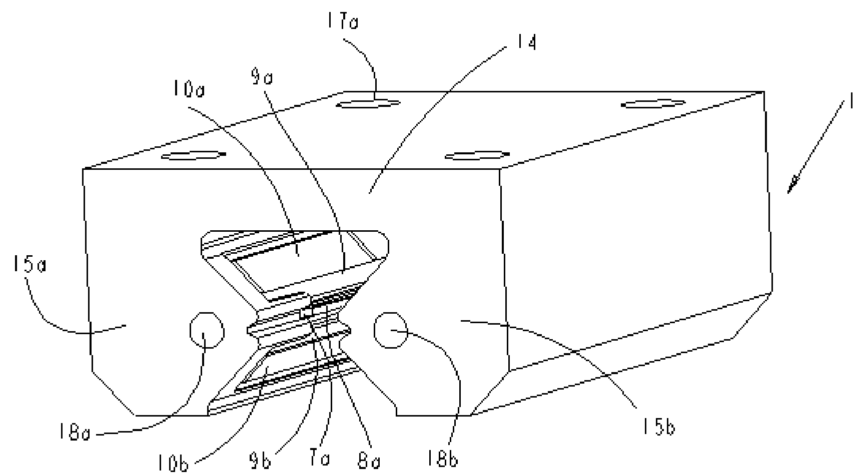
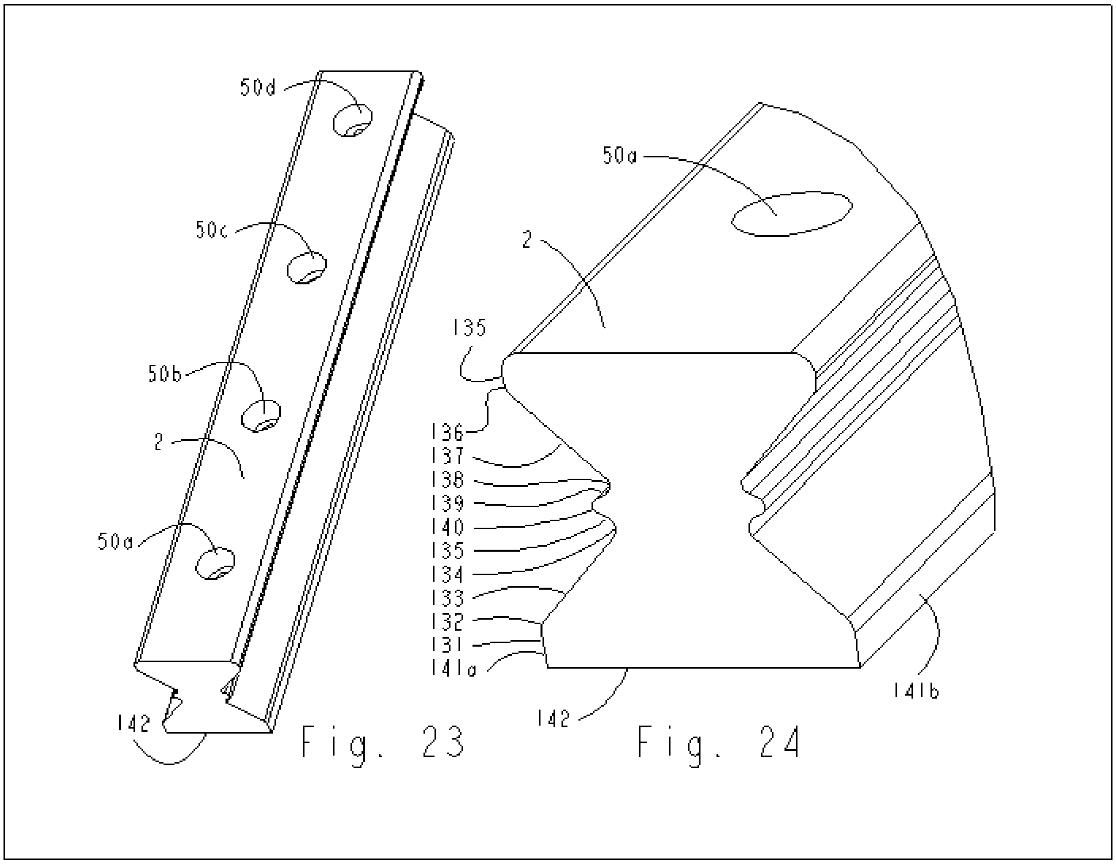


Fig. 20

SCALE : 0.012 TYPE : PART NAME : HGTRUCK SIZE : A

[2] Patents pending. Aesop, Inc. PO Box 2126, Concord, NH 03302-2126, Fax 603-224-5369

- **The small protrusion on the rail center acts as the surface self compensation system:**



SCALE : 0.007 TYPE : PART NAME : HGRAIL SIZE : A

Performance of a size 45 HydroRail™ bearing verses a high end rolling element linear guide.

The HydroRail™ Vs. a high end rolling element bearing		***Size 45, @1190 psi HydroRail™ Bearing*** Nominal gap = 0.001 in.			***Size 45 Rolling Element Bearing*** Ultra Precision, 0.03 Preload		
		Compress.	Tension	Lateral	Compress.	Tension	Lateral
Static Load which causes permanent damage	lb	250,000[1]	75,000	110,000	29,750[5,7]	29,750	29,750
Dynamic Load Capacity at given Life	lb	2,500[2,3]	2,500	6,500	3,000[6,7]	3,000	3,000
Life	km	no limit			1,000		
Static Stiffness	lb/µin	3.0[3]	2.7	4.6	5.1[7]	4.7	7.1
Dynamic Stiffness at Resonance	lb/µin	2.0[3,4]	1.8	3.0	0.8[8]	0.8	1.1
Q (Damping Factor)	-	1.5[4]			6.2[8]		
Maximum Speed	m/s	no limit			2[7]		
Maximum Acceleration	m/s^2	no limit			50[7]		
Static Friction	lb	none			3.2[7]		
Motion Resolution	µin	infinite			40[10]		
Friction @ 0.5 m/s	lb	4.2[3]			9.4[7]		
Friction Power @ 0.5 m/s	W	9.4[3]			21.0[7]		
Straightness (over 15.5 inches travel)[9]	µin	20[4]			45[8]		
Straightness Repeatability	µin	8[4]			17[8]		
Hydraulic Oil Flow (m=76 cSt @ 90 F)	gpm	0.2[3]					
Pumping Power required	W	100[3]					

[1]Will cause permanent carriage deformation according to FEA analysis
[2]Load which causes 50% closure of bearing gap
[3]From fluid circuit mathematical model
[4]Based on data from past non-modular hydrostatic bearings designed at MIT
All analysis done by Nathan R. Kane at MIT

[5]Will cause permanent deformation of rollers and races
[6]Equal to theroetical dynamic load divided by load factor of 3 to account for the most demanding applications
[7]Based on product catalogue data
[8]Based on experimental data obtained by Nathan R. Kane at MIT

[9] Defined as max. deviation of carriage relative to rail reference edges
[10] Quantity shown is typical for rolling element guides, according to S. Futami, A. Furutani, and S. Yoshida, “Nanometer Positioning and its Microdynamics,” Nanotechnology, Vol. 1, No. 1, 1990, pp.31-37

Technical advantages and tradeoffs associated with the HydroRail™

HydroRail™ Feature	Benefits for Various Applications
Very high "crash" resistance	Greatly reduces the chance that a crash will result in expensive downtime for bearing repair.
Potentially infinite bearing life	If fluid filter is replaced regularly, cost of rebuilding linear ways can be eliminated.
High damping	Reduces problematic chatter, increases surface finish.
Zero static friction	Reduces servo reversal error; increases motion resolution, allowing 20 μin infeeds or smaller.
Low dynamic friction	Reduces heat generation and hence reduces thermal errors at high speeds.
High Straightness	Results in straighter surfaces, more accurate parts.
Swarf particles can pass freely through bearing gap	Virtually immune to the extremely destructive effects of ceramic swarf when grinding ceramic materials. Allows bearing to remain accurate over several years of operation without a rebuild.

Estimated Carriage and Rail Costs				
Bearing Size	**35**	**45**	**55**	**65**
Per Carriage	$570	$600	$650	$700
Per meter of rail	$770	$800	$850	$900

Fluid System Cost	
To Power 4 Carriages of any size	$3,800
To Power 8 Carriages of any size	$4,800
To Power 12 Carriages of any size	$5,600

[1] Estimates are based on an ultra precision rolling element linear guide system with similar manufacturing complexity
[2] Includes DC permanent magnet motor (1 hp per 4 carriages), power supply, gear pump, 3μm high pressure filter, properly sized oil chiller with a 10 gallon tank, pressure relief value, a pressure measurement and control system, 10 foot hydraulic hose, and 15 gallons of hydraulic oil. Does not include fittings and hoses going to individual trucks, fluid gutters and drains, or a way protection system such as bellows.

New Possibilities for Machine Tool Manufacturers

- **Offer "Check the Box" Hydrostatics to Customers Buying a New Machine**

  Linear Bearing Option: ☐ Standard Linear Guides ☑ HydroRail™ Hydrostatic Linear Guides

- **Upgrade an Entire Product Line Quickly and Inexpensively**
  With minimal additions (such as adding drainage gutters for hydraulic oil), an old product line that uses standard linear guides can be rejuvenated by equipping the machines with HydroRail™ bearings.

- **Introduce A New Ultra Performance Machine Tool Which is Very Cost Competitive**
  Design a new ultra performance high speed machining center which takes full advantage of the performance capabilities of the HydroRail™ bearing. Promote the unique "crash" resistant, accuracy enhancing, and long bearing life features, and also the high value added to the machine tool by the HydroRail™ technology, which translates directly into a great value for the customer.

- **Replace Costly Hand Scraped Way Systems**
  In an effort to reduce assembly time and costs, countless machine tool manufacturers have spent thousands of R&D dollars trying to make rolling element guides work for them, only to give up and go back to using their old labor intensive, costly custom way systems (such as sliding and hydrodynamic systems which require hand scraping). For many of these companies, the HydroRail™ can offer the ultra high performance they require while also providing them with much of the savings that they are looking for.

New Possibilities for Machine Tool Users

- **Retrofit a Machine to Bring it to A New Level of Accuracy**
  During a rebuild, a machine that uses standard linear guides can be economically upgraded to HydroRail™ bearings. For a modest investment, the machine can then can perform at a new level of accuracy.

- **Retrofit a Machine to Greatly Increase Bearing Life in Abrasive Environments**
  When grinding ceramics or other hard materials, the abrasive swarf created always gets past even the best bearing seals, and then quickly wears the surfaces of rolling elements and races. Retrofitting such a machine with HydroRail™ bearings can eliminate this problem, since the bearing gap is large enough to allow swarf particles to pass through freely.