Linear Rolling Bearings

ME EN 7960 – Precision Machine Design
Topic 8

Bearings

- Bearings are mechanical elements that free one or more of the six degrees of freedom while constraining the remainders
- Bearings can be classified in two main ways
  1. Degrees of freedom (linear, rotary)
  2. Contact yes or no (contact, non-contact)

Non-Contact Bearings

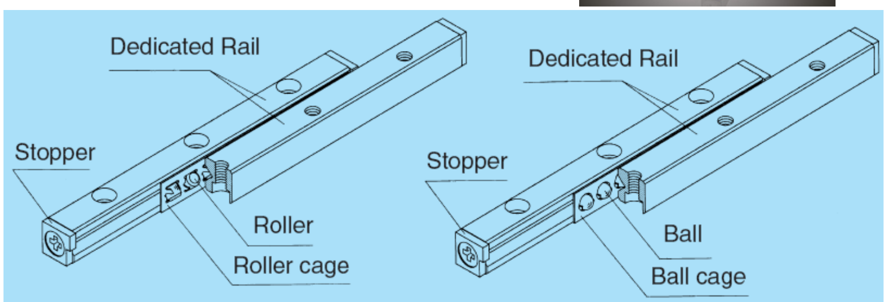
- Non-contact bearings maintain a gap between the moving surfaces, thereby avoiding any kind of contact
- The gap is maintained through:
  - Pressurized medium (air, water, oil)
  - External forces (magnetic forces)
- Non-contact bearings are used in precision machinery where accuracy and speed requirements prohibit the use of contact bearings
  - Hydrostatic: high-speed machining spindles
  - Aerostatic: slides for coordinate measuring machines (CMM), dental drills. Also: read head of hard disks.
  - Magnetic bearings: high-speed trains (Transrapid)

Contact Bearings

- Contact bearings can be grouped in two main categories according to their type of contact:
  1. Rolling contact bearings
  2. Sliding contact bearings
- Rolling contact bearings separate the mechanical components through the use of balls or rollers
- Sliding contact surfaces make contact, either with or without lubrication

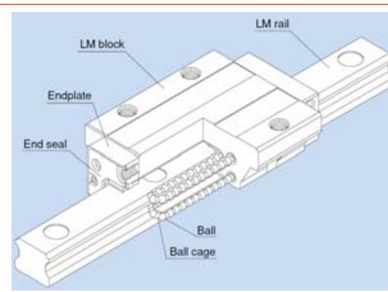
Basic Types

- There are three main types of rolling element linear motion bearings:
  - Non-recirculating balls or rollers
  - Recirculating balls
  - Recirculating rollers



Source: THK

Recirculating Linear Bearings



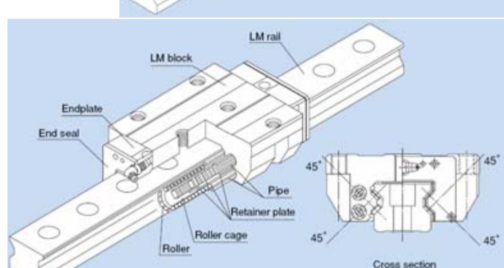


Fig. 1 Structure of Model SRG

Source: THK

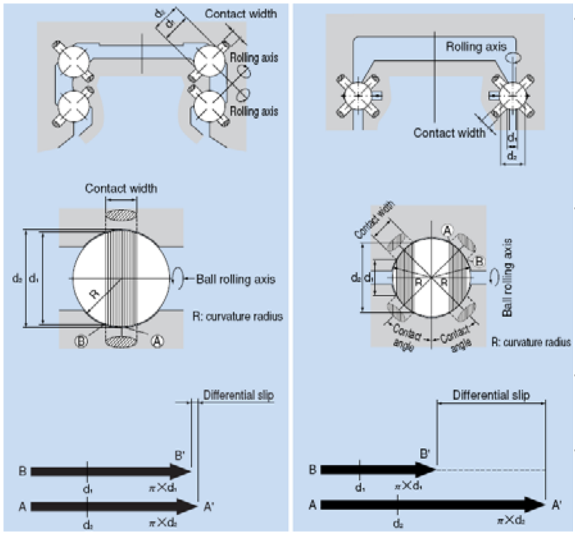
General Design Considerations

- 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
- Bear in mind many of the fine points of general characteristics of rotary motion bearings

Balls or Rollers?

- Balls can be made to higher accuracies
- 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!

Circular groove vs. gothic arch



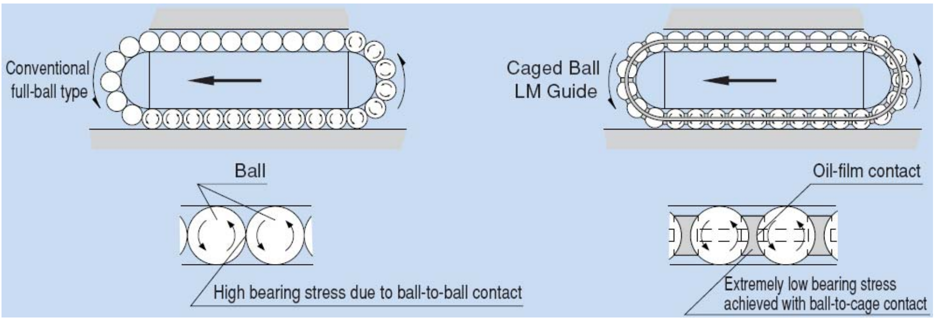
- When the ball rotates one revolution, the ball slips by the difference between the circumference of the inner contact area (πd_1) and the of the outer diameter (πd_2)
- If the difference is large, the ball rotates while slipping and the friction coefficient increases up to 10 times, causing increases resistance and wear
- Circular grooves have 3% slip, gothic arches up to 40%
- Gothic arces have larger contact area
  - More damping

Source: THK

To Recirculate or to Not 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 the balls in a polymer necklace that keeps the balls spaced, and helps to keep them lubricated

THK NR Series



- This reduces rolling element noise by 50%
- This increases maximum speed to up to 4 m/s

- 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

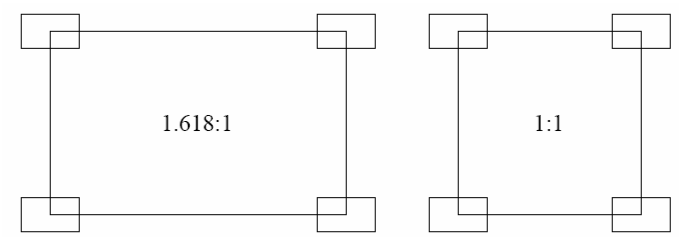
Source: THK

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)

Bearing Spacing (contd.)

- 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

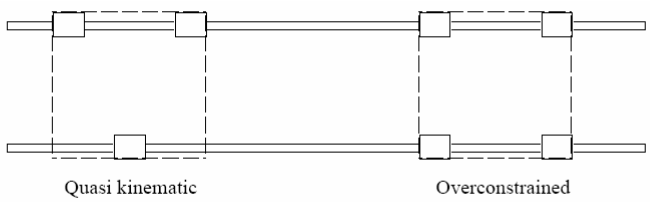
Source: Alexander Slocum, *Precision Machine Design*

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

Detailed Design Considerations

- 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:



Source: Alexander Slocum, *Precision Machine Design*

Design Considerations

- 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 catalogs is usually for 100 km of travel
    - The load/life relation is cubic:

$$F_{design} = F_{100km}\left(\frac{L_{design,100km}}{100km}\right)^{-1/3}$$

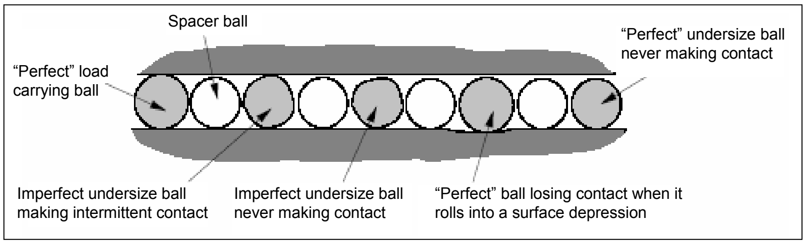
    - At 1000 km, the load capacity is $0.46F_{100km}$!

Design Considerations

- 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 $2\pi D_{ball}$

Source: Alexander Slocum, *Precision Machine Design*

Accuracy (contd.)

- 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

Preload

- Prevents lost motion upon load reversal
- If an un-preloaded 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

Preload for Recirculating Linear Ball Bearings

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 cantilevered loads. Better for higher 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 measuring 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

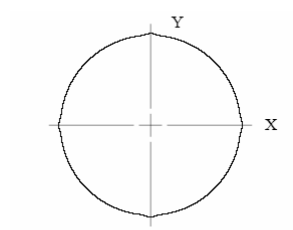
Source:THK Corporation

Characteristics

- 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:



Source: Alexander Slocum, *Precision Machine Design*

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

Friction (contd.)

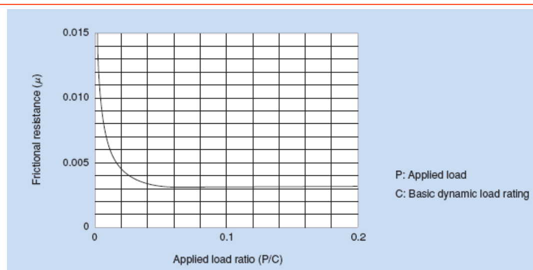


Fig. 8 Relationship between Applied Load Ratio and Frictional Resistance

Table 5 Frictional Resistances (μ) of LM Systems

Types of LM systems	Representative types	Frictional resistance (μ)
LM Guide	SSR, SHS, SNR/SNS, SRS, RSR, HSR, NR/NRS	0.002 to 0.003
	SRG, SRN	0.001 to 0.002
Ball Spline	LBS, LBF, LT, LF	0.002 to 0.003
Linear Bush	LM, LMK, LMF, SC	0.001 to 0.003
LM Stroke	MST, ST	0.0006 to 0.0012
LM Roller	LR, LRA	0.005 to 0.01
Flat Roller	FT, FTW	0.001 to 0.0025
Cross-roller Guide/Cross-roller Table	VR, VRU, VRT	0.001 to 0.0025
Linear Ball Slide	LS	0.0006 to 0.0012
Cam Follower/Roller Follower	CF, NAST	0.0015 to 0.0025

- Friction decreases with increased load until the applied load is roughly 6% of the dynamic load rating
- Higher loads do not increase the friction further.
- Ball bearings have lower friction compared to rollers (0.002 - 0.003 for balls vs. 0.005 - 0.01 for rollers)

Source: THK

Friction (contd.)

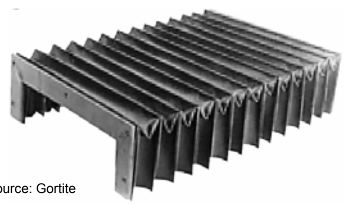
- It is important to use cover plugs on linear guide rail bolt holes
- Seals passing over open holes produce varying friction loads, and can let dirt get into the bearings

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

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
- Folded bellows have little to no friction but may fatigue and also easily trap chips on the outside
- Metal sliding covers are smooth on the outside to help deflect chips and coolant but exhibit friction



Source: Gortite

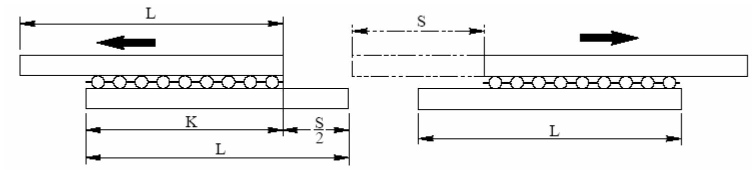
Source: MPC, Milwaukee Protective Covers

Support Equipment

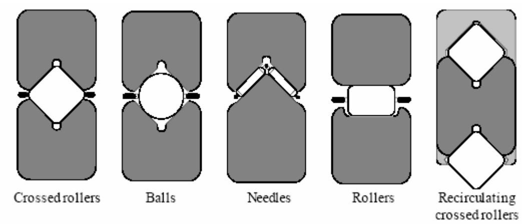
- Many units are sealed for life
- Some units require a periodic application of grease
- For very high cycles (as on a high speed machining center), an oil lubricator should be installed
- Where does the oil go?
  - Design in oil collection gutters into the machine casting
  - This will also facilitate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

Non-Recirculating Crossed Roller Bearings

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



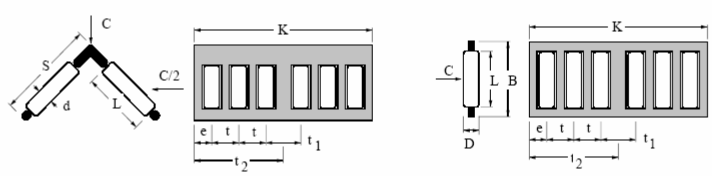
There are many variations on this design:



Source: Alexander Slocum, *Precision Machine Design*

Non-Recirculating Crossed Roller Bearings (contd.)

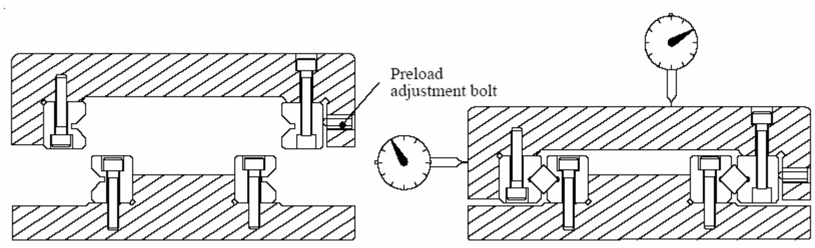
- There are many other variations of non-recirculating linear motion roller bearings
- Typically available modular non-recirculating roller linear bearings (Courtesy of Schneeberger Inc.):



Source: Alexander Slocum, *Precision Machine Design*

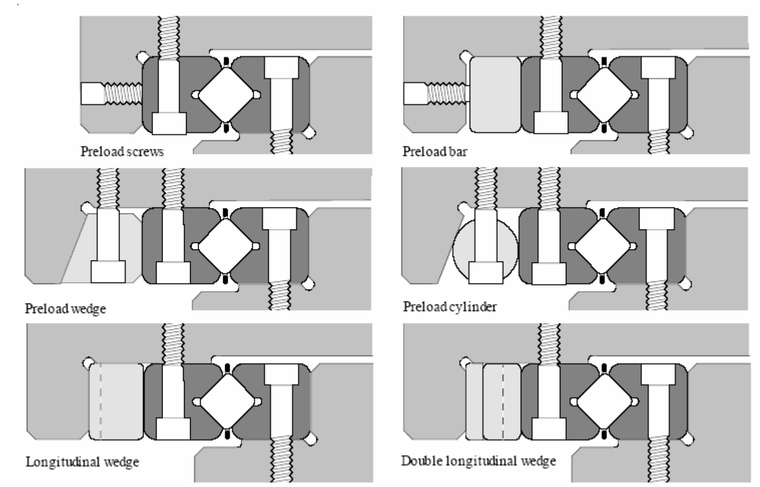
Assembly

- Typical assembly of crossed roller supported slide:



Preload Methods

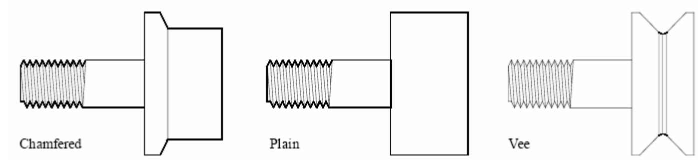
- Methods for preloading crossed roller bearings:



Source: Alexander Slocum, *Precision Machine Design*

Wheels on Rails

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

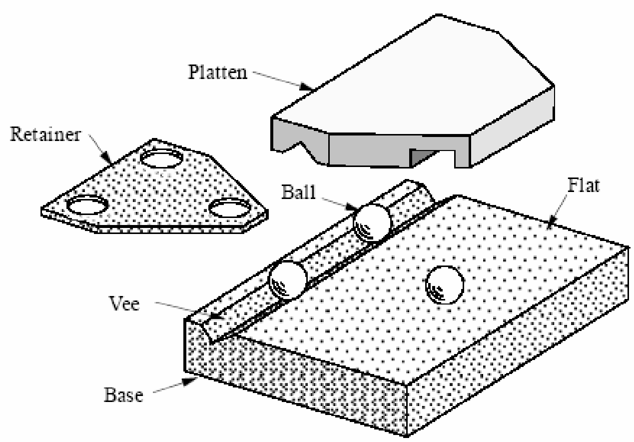


- Kinematic configurations of instrument ball bearings on polished ceramic rails can yield sub-micron performance for a very low cost
- Beware of the formation of frictional polymers on dry-running systems
  - As elements roll, they compress organic molecules in the air onto the surface and build up a layer
  - This layer is not uniform and causes a bumpy ride and velocity control problems

Source: Alexander Slocum, *Precision Machine Design*

Kinematic Systems

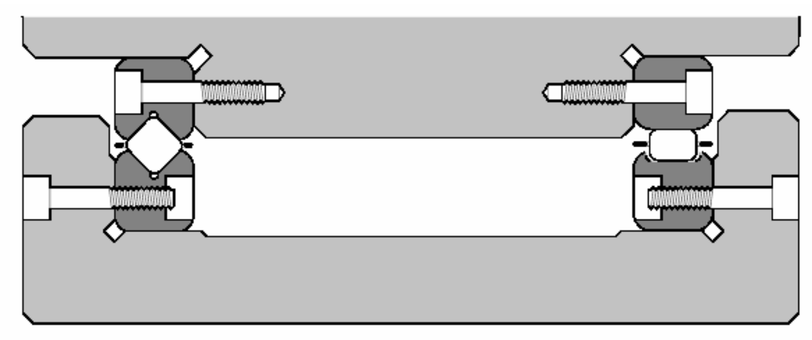
- Kinematic designs are often used:



Source: Alexander Slocum, *Precision Machine Design*

Kinematic Systems (contd.)

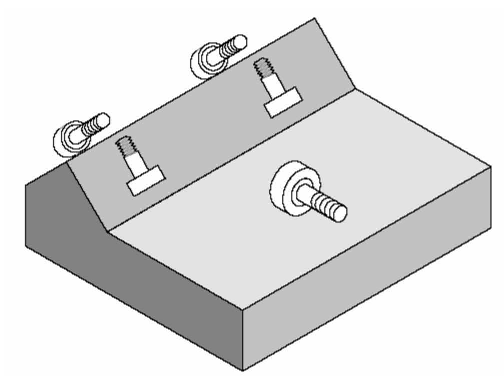
- Quasi-kinematic arrangement of crossed roller bearings and rollers on flat rails:



Source: Alexander Slocum, *Precision Machine Design*

Kinematic Systems

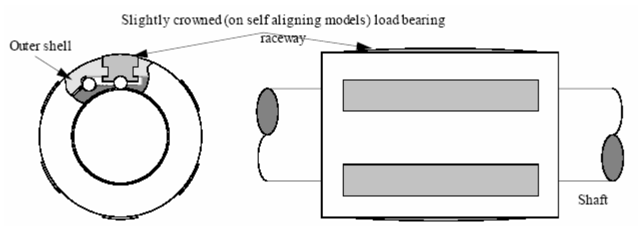
- Concept for a cam-roller based kinematic design (crowned rollers must be used if slip-noise is to be avoided)



Source: Alexander Slocum, *Precision Machine Design*

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.):



Source: Alexander Slocum, *Precision Machine Design*

Ball Bushing Bearings (contd.)

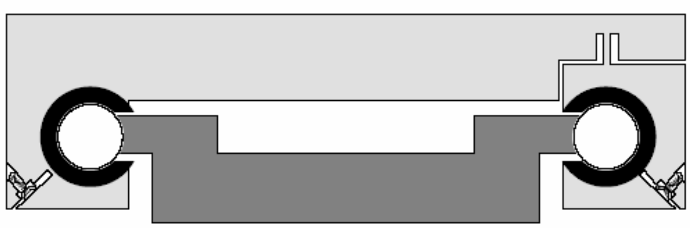
- Round shafts are inexpensive to grind or hone
- Easy to design and manufacture machines using Ball Bushing™ bearings
- Rotary and torque transmitting designs are available
- Generally intended as a modest accuracy bearing (material handling devices), counterweight guides)

Ball Bushing Bearings (contd.)

- 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)

Ball Bushing Bearing (contd.)

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



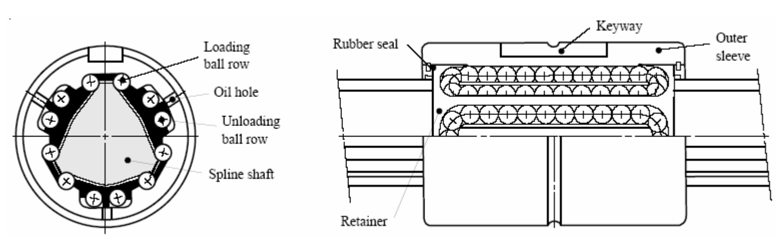
Source: Alexander Slocum, *Precision Machine Design*

Ball Bushing Bearings (contd.)

- 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.):

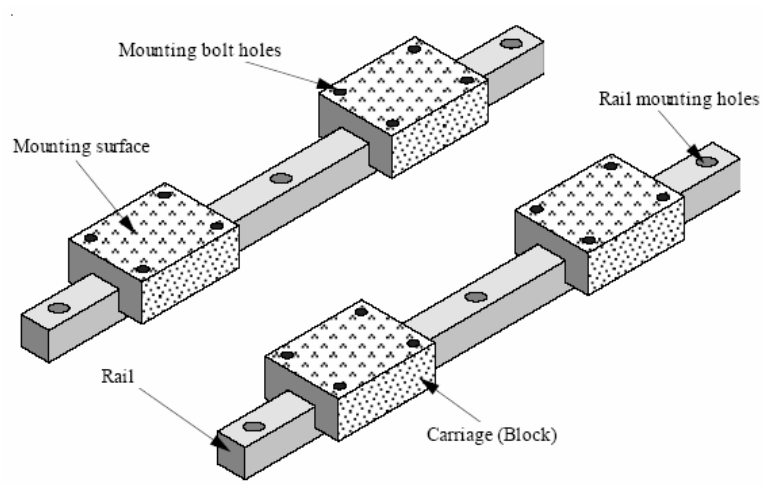


Source: Alexander Slocum, *Precision Machine Design*

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:

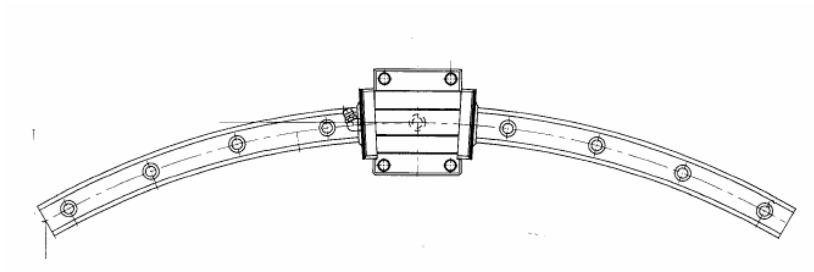
Linear Motion Guides



Source: Alexander Slocum, *Precision Machine Design*

Linear Motion Guides

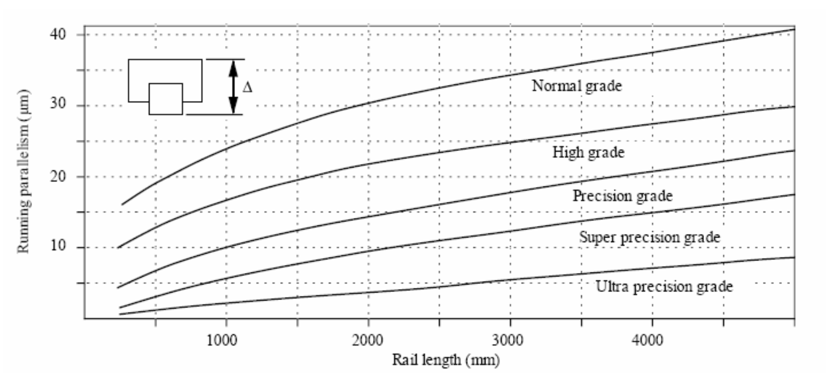
- Specialized Linear Guides are available for curved paths, and also with integral gear racks for long range of motion machines (from THK Corp.)



Source: Alexander Slocum, *Precision Machine Design*

Linear Motion Guide

- Typical running parallelism of linear guides:



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

Source: Alexander Slocum, *Precision Machine Design*