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

Recirculating Linear Bearings

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 ($\pi d_1$) and the of the outer diameter ($\pi d_2$)

• 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 arches 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:

![Diagram]

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:

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

- 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 $D_{\text{ball}}$, $\pi D_{\text{ball}}$, and $2\pi D_{\text{ball}}$

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

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

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.

<table>
<thead>
<tr>
<th>Bearing</th>
<th>“Dimple” size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding contact</td>
<td>10 – 20 μm</td>
</tr>
<tr>
<td>Recirculating rolling element</td>
<td>3 – 5 μm</td>
</tr>
<tr>
<td>Crossed rollers</td>
<td>1 – 2 μm</td>
</tr>
<tr>
<td>Hydrostatic or aerostatic</td>
<td>0 μm</td>
</tr>
</tbody>
</table>

Friction (contd.)

- 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).

Table 5: Frictional Resistances (μ) of LM Systems

<table>
<thead>
<tr>
<th>Types of LM systems</th>
<th>Representative Items</th>
<th>Frictional resistance (μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM Guide</td>
<td>SBR, SBRX, SBRX3, SBR, SBRX, MR, MRX</td>
<td>0.002 to 0.003</td>
</tr>
<tr>
<td>Ball Spline</td>
<td>LSR, LSR-1, LF</td>
<td>0.005 to 0.008</td>
</tr>
<tr>
<td>Linear Bush</td>
<td>LM, LML, LR, SC</td>
<td>0.004 to 0.006</td>
</tr>
<tr>
<td>LM Spline</td>
<td>MR, ST</td>
<td>0.0006 to 0.0012</td>
</tr>
<tr>
<td>LM Roller</td>
<td>LSR, LSR-1</td>
<td>0.005 to 0.011</td>
</tr>
<tr>
<td>Flex Roller</td>
<td>FT, FTW</td>
<td>0.001 to 0.0025</td>
</tr>
<tr>
<td>Crossroller Spline/Cones roller Table</td>
<td>VL, VHL, VST</td>
<td>0.006 to 0.0025</td>
</tr>
<tr>
<td>Linear Ball</td>
<td>L3</td>
<td>0.00005 to 0.00012</td>
</tr>
<tr>
<td>Cam Follower/Block Follower</td>
<td>OF, NAST</td>
<td>0.0015 to 0.0025</td>
</tr>
</tbody>
</table>

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 transmit 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

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:

- Crossed rollers
- Balls
- Needles
- Rollers
- Recirculating crossed rollers

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.):
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:
Kinematic Systems (contd.)

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

Source: Alexander Slocum, Precision Machine Design

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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.):

![Ball Bushing Bearing Diagram](image)

Source: Alexander Stocum, 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.):
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 Stocum, 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