Lecture 15

Rolling Element Bearings for Linear Motion

Outline

• Introduction
• Characteristics of rolling element linear bearings
• Types of linear bearings
Linear Rolling Bearings

- Linear bearings are bearing elements for translation type motion.
- Linear rolling bearings are available as monorail guidance systems, track roller guidance systems, shaft guidance systems with linear ball bearings, flat cage guidance systems, guidance systems with linear recirculating roller or ball bearing units and as driven units (actuators and tables).

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:
Linear Rolling Element Bearing Configurations

Non-recirculating 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:

  - 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 most of the balls in a polymer necklace that keeps the balls spaced, and helps to keep them lubricated.

Friction of the balls

<table>
<thead>
<tr>
<th>Conventional type (Full ball type)</th>
<th>Now type (With a retainer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball</td>
<td>Ball</td>
</tr>
<tr>
<td>Typical point contact</td>
<td>Oil film contact</td>
</tr>
</tbody>
</table>

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

To Recirculate or not to Recirculate?

- 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).

Bearing Spacing

• 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.

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 showing quasi kinematic and overconstrained arrangements]
Detailed Design Considerations

- 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?

Detailed 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 catalog is usually for 100 km of travel.
  - The load/life relation is cubic:
    $$ F_{\text{at desired travel}} = F_{100 \text{ km rated load}} \left( \frac{L_{de \sin km}}{100 \text{ km}} \right)^{-1/3} $$
Detailed Design Considerations

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

Detailed Design Considerations

- 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.
Detailed Design Considerations

• Rolling elements are not necessarily round and of the same size:

- Look for noise spikes at $D_{ball}$, $\pi D_{ball}$, 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.

Fourier transform of a linear guide's straightness errors:
Detailed Design Considerations

• 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.

Preload

• 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.
Preload

- 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

- **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

- 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.

Motion Error

- Errors will appear at velocity crossovers:

<table>
<thead>
<tr>
<th>Bearing</th>
<th>&quot;Dimple&quot; 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>
Motion Error

• 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.*

Wind up

• **Wind up** is such a phenomena, which is caused by the interaction of integral action and saturations. All actuators have limitations: a motor has limited speed, a valve cannot be more than fully opened or fully closed, etc. For a control system with a wide range of operating conditions, it may happen that the control variable reaches the actuator limits.
• When this happens the feedback loop is broken and the system runs as an open loop because the actuator will remain at its limit independently of the process output. If a controller with integrating action is used, the error will continue to be integrated. This means that the integral term may become very large or, colloquially, it “winds up”. It is then required that the error has opposite sign for a long period before things return to normal. The consequence is that any controller with integral action may give large transients when the actuator saturates.
Wind up

- Controllers should have “Anti-Reset Wind up” algorithms incorporated into their designs to prevent this from happening.

Thermal performance

- 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?

- 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

• 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.

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:

Non-recirculating Crossed Roller Bearings

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

- Typical assembly of crossed roller supported slide:

Mounting

- 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

- Kinematic designs are often used:
Quasi-kinematic Designs

• Quasi-kinematic arrangement of crossed roller bearings and rollers on flat 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):
Ball Bushing Bearings

- 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).
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.):

Ball Splines

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

• While in rolling bearing arrangements the bearing elements are separated by rolling parts (the rolling elements), in plain guidance systems the movable component slides on a static guideway or shaft. Depending on the type of guidance system, the sliding layer is applied to the movable or the rigid component. Lubrication is carried out by means of lubricants embedded in the sliding layer.

• Linear plain bearings are linear locating bearings for unlimited stroke lengths. These linear guidance systems are available as a miniature plain guidance system.
Linear Plain Bearings

- Plain bearing guidance systems have low wear and high static load capacity, are insensitive to shocks and contamination, make little noise and operate substantially free from stick-slip.
- Maintenance-free plain guidance systems do not require lubrication, and low-maintenance materials have good emergency running characteristics.
- Due to their versatile specific characteristics, plain guidance systems are used in many areas, especially where the bearing position must be maintenance-free or low-maintenance, there is a risk of inadequate lubrication or where lubricant is either undesirable or impermissible.

Linear Plain Bearings

- The life of a linear plain guidance system depends essentially on the load, sliding speed, temperature and operating duration. There are additional limiting factors including contamination, corrosion in dry running or possible ageing of lubricant if lubrication is not sufficient.
Rolling Bearing

http://www.fag.com