Precision Machine Design

Topic 14

Sliding contact bearings

Purpose:

Sliding bearings are the oldest and most common type of linear bearing. They are also useful in low-speed rotary applications on large diameters, and higher speeds at smaller diameters. This lecture presents design theory of sliding bearings as well as commonly used designs.

Outline:

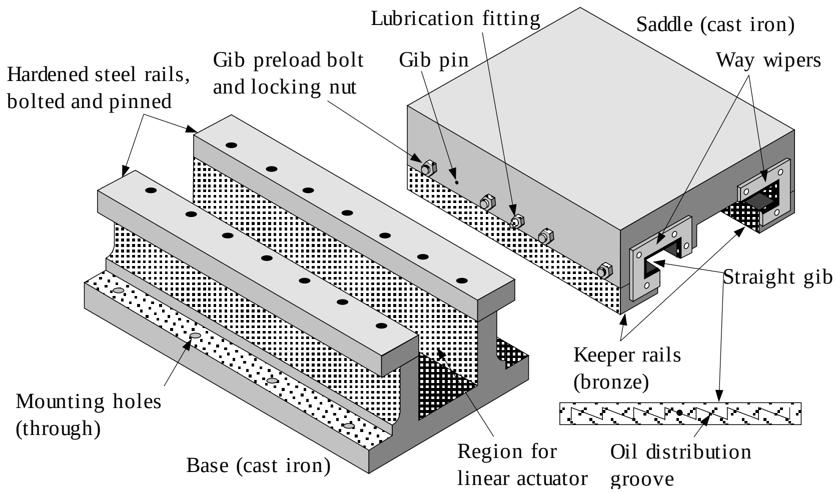
- **General properties**
- **Design considerations**
- **Replicated bearings**

"A hen is only an egg's way of making another egg"

Samuel Butler

General characteristics

- **Sliding contact are the "original" machine tool bearings.**
- **They are very robust and reliable.**
- **They are speed limited and have friction-induced servo limits.**
- **They are economical and for many applications will never be replaced.**



Speed and acceleration limits

- **< 15 m/min (600 ipm) and 0.1 g.**

Applied loads

- **Large surface area allows for high load capacity.**
- **Virtually insensitive to crashes.**

Accuracy

- **Axial: 5 - 10 microns depending on the drive system.**
- **Lateral (straightness): 0.1 - 10 microns depending on the rails.**
- **Special designs can yield nanometer accuracy.**

Repeatability

- **Axial: 2 - 10 microns depending on the drive system.**
- **Lateral (straightness): 0.1 - 10 microns depending on the rails.**

Resolution

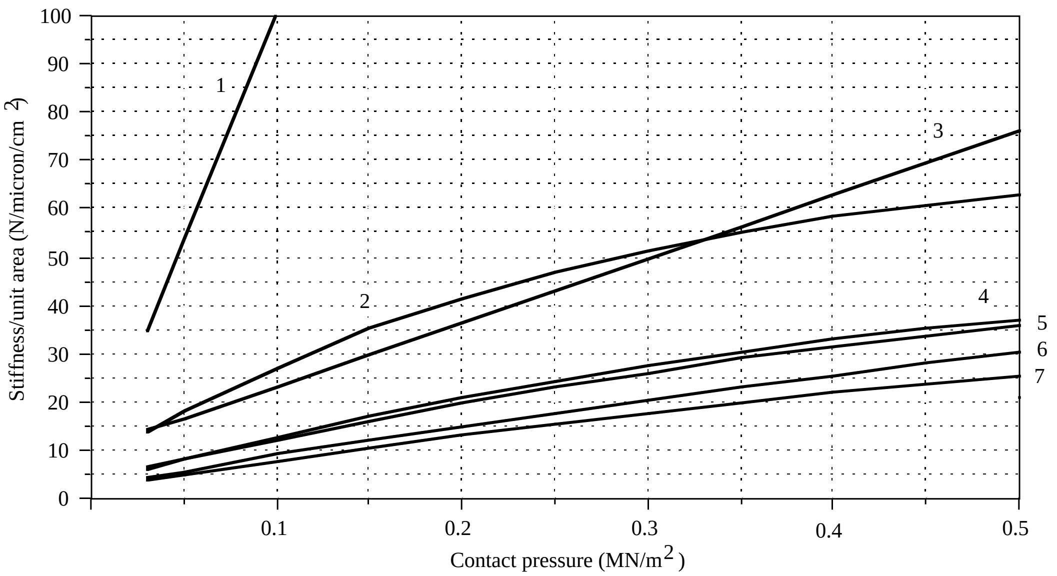
- **Axial: 1 - 10 microns depending on the drive system.**

Preload

- **5-10% of the allowable load.**

Stiffness

- **Easily made many times greater than other components in the machine.**
- **Stiffness of various sliding contact bearings lubricated with light oil and after wear-in.** (After Dolbey and Bell.)



#	Way	Bearing	Stiffness/unit area (k/a) as a function of contact pressure P
1	Lapped cast iron	Ground cast iron	k/A = 6.2105 + 9.5583e-4P
2	Ground cast iron	Ground cast iron	k/A = 7.2247 + 2.3291e-4P - 3.4428e-10P^2 + 2.0422e-16P^3
3	Ground cast iron	Scraped cast iron	k/A = 10.129 + 1.3275e-4P
4	Ground cast iron	Ground ferobestos	k/A = 3.4536 + 9.7855e-5P - 5.5217e-11P^2 - 1.0544e-17P^3
5	Ground cast iron	Ground plain DX	k/A = 3.8624 + 8.7409e-5P - 3.7974e-11P^2 - 1.8380e-17P^3
6	Ground cast iron	Ground dimpled DX	k/A = 2.1344 + 7.5302e-5P - 5.8759e-11P^2 + 4.2540e-17P^3
7	Ground cast iron	DU as received	k/A = 2.1064 + 6.1535e-5P - 3.0397e-11P^2 + 2.2446e-18P^3

Vibration and shock resistance

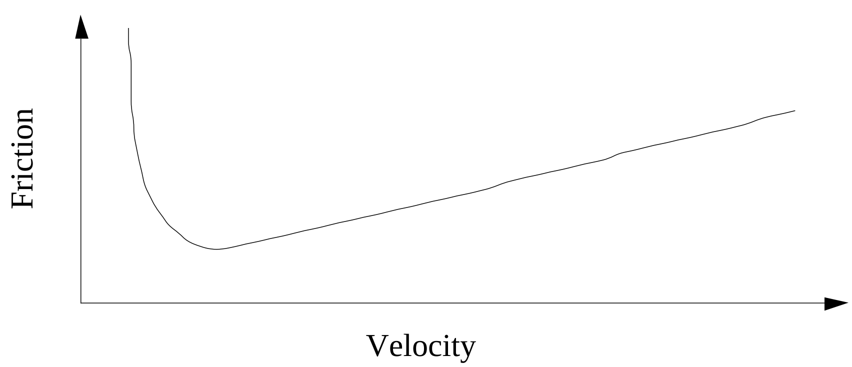
- **Excellent.**
- **Matched only by hydrostatic and hydrodynamic bearings.**

Damping capability

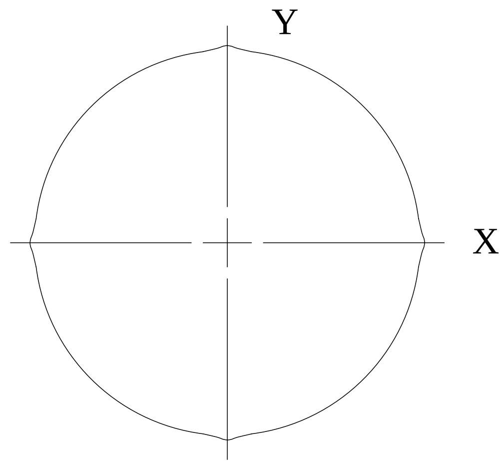
- **Excellent normal to direction of motion due to squeeze film damping.**
- **Matched only by hydrostatic and hydrodynamic bearings.**
- **High along direction of motion.**
- **Predict it using squeeze film damping theory.**

Friction

- **Static friction *never* equals dynamic friction.**
- **Most data is supplied for speed ranges from 10^{-6} m/s and 0.1 m/s, but what about at 0 m/s!**
- ***Stiction*, when static μ is greater than dynamic μ, cause stick-slip which causes position errors.**
- **Friction initially high, then lower, then increases (viscous effects): *Stribeck curve*:**



- **Static friction is always greater than dynamic friction.**
- **This effects the system's controllability.**
- **With linear scales, as opposed to an encoder on a ballscrew, dimples will appear at velocity crossovers.**
- **Example: An end mill moved in X and Y to form a hole:**



- **Linear encoder allows the I term in a PID controller to build up as the ballscrew deforms elastically and the table remains stationary.**
- **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[1]:**
    - **The controller decreases the integrator gain at zero velocity.**

[1] Prof. Tomizuka at University of California Berkeley is an expert in control algorithms to minimize dimples.

Thermal performance

- **High friction coefficient generates heat.**
    - **The bearings are so stiff, that when thermal errors (e.g., bowing), high points are created which wear and crash the bearing.**
- **Heat changes oil viscosity.**
- **Large surface area efficiently transmits heat.**
- **In extreme cases, consider using a thermocentric design (see PMD Section 8.7):**
    - **Expansion in one direction relieves expansion in another direction.**

Environmental sensitiveness

- **Particles embed themselves in softer surface or roll out.**
- **Generally very tolerant of foreign matter.**
- **Water absorption can be dealt with the use of a sealant.**

Seal-ability

- **Wiper seals are often sufficient and easily fitted.**
- **Don't tempt fate, use way covers or bellows if possible.**

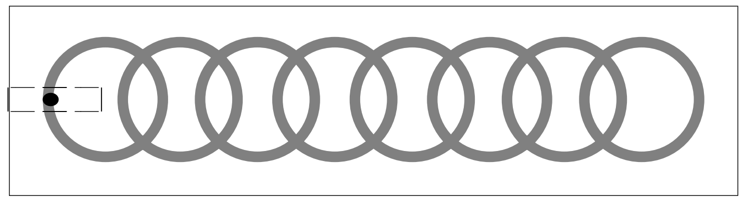
Size and configuration

- **Thin profile.**
- **Virtually any configuration possible.**

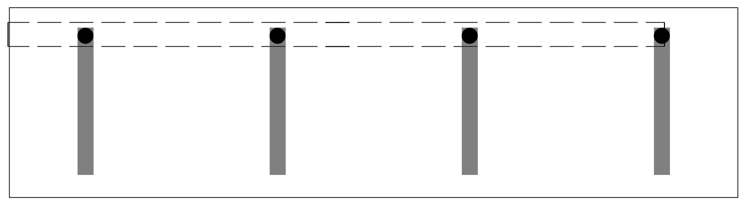
Support equipment

- **Automatic lubricator needed to periodically lubricate.**
- **Grooves are required to distribute the lubricant:**

Longitudenal grooves can act as leakage paths and
starve transverse grooves



"Pure" transverse grooves require deep hole drilling for supply



  - **Scraped surfaces hold pockets of oil and are optimal for lubrication.**
  - **Grinding with a cup wheel can also create an effective cross-hatch pattern.**
- **Varying fluid resistances can cause straightness errors to be a function of lubricator cycle.**
  - **Controller can signal lubricator when machine is idling.**

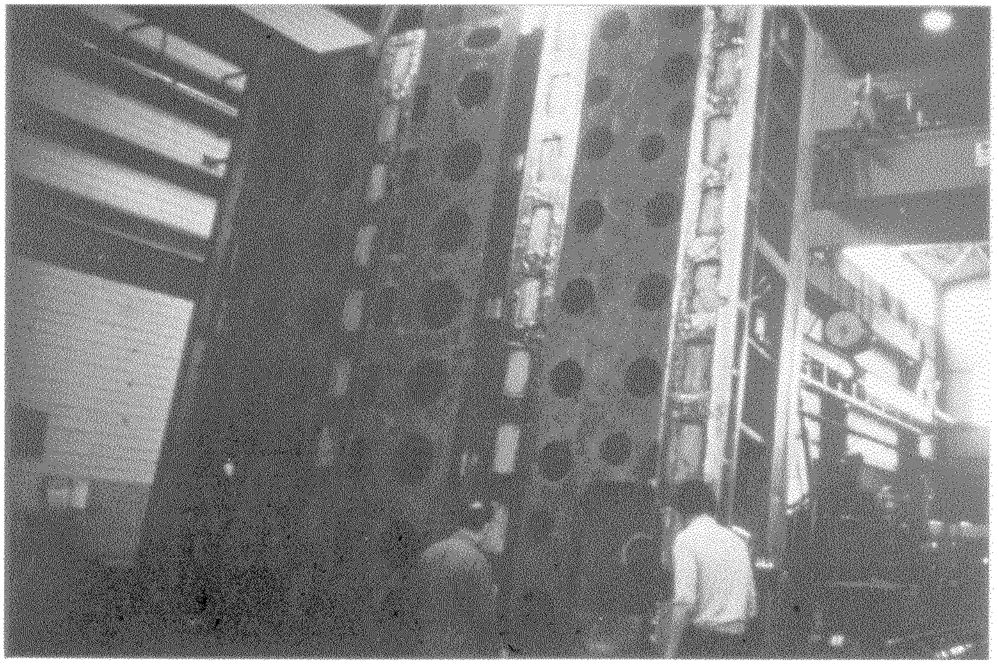
Maintenance

- **Generally requires periodic lubrication.**
  - **Lubricators periodically send a squirt of oil that can cause a displacement if design is not done carefully.**
  - **Differential flow to different bearings will cause a differential displacement.**
- **Instrument grade bearings can often be run dry.**

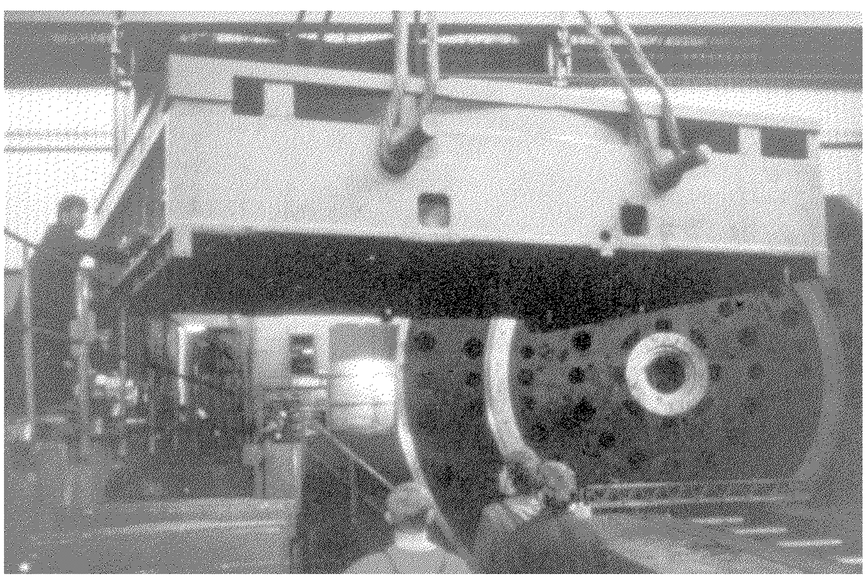
Replicated bearings

- **Only the replication master needs to be accurately finished.**
  - **An exact fit is obtained, so gibs are usually not needed.**
- **The machine is easily rebuilt by casting a bearing.**
  - **Replicated bearings generally do not have to be hand finished.**
- **Care must be taken to manage the heat generated during the cure process or else the system may harden in a warped state**
  - **Part and master should have same thermal time constant to prevent gradients and warping.**
- **Replicants typically shrink about 0.2-0.3%, which is often referred to as "negligible" (e.g., 3mm*0.002 = 6μm).**
- **The resin should be degassed before injection.**
- **Several manufacturing applications with replicated bearings are presented here to illustrate the technique.**

- **Replicating bearings for a 55 ton support, all guideways coated with Moglice™** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).

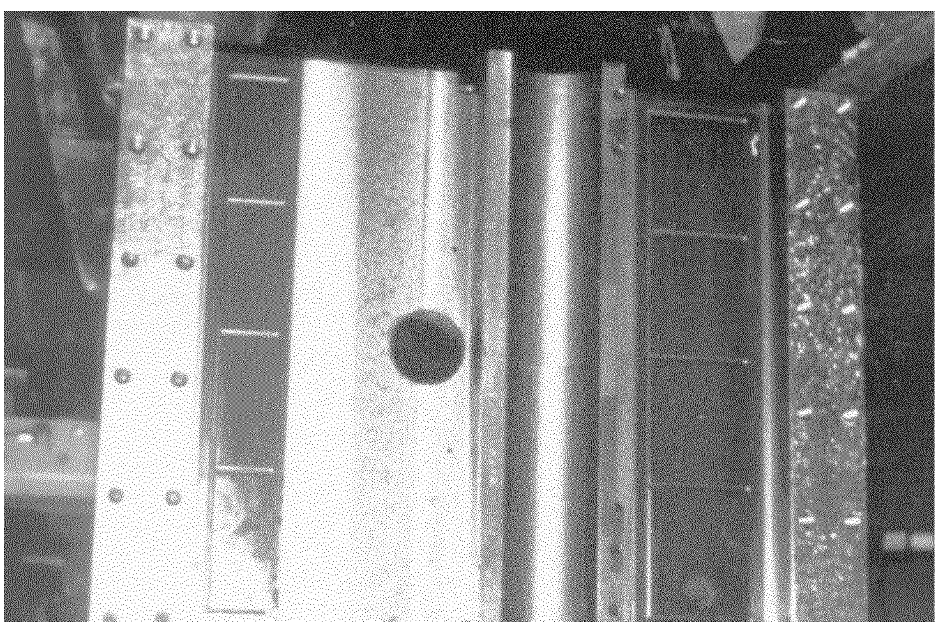


- **Coated support being put onto the bed** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).

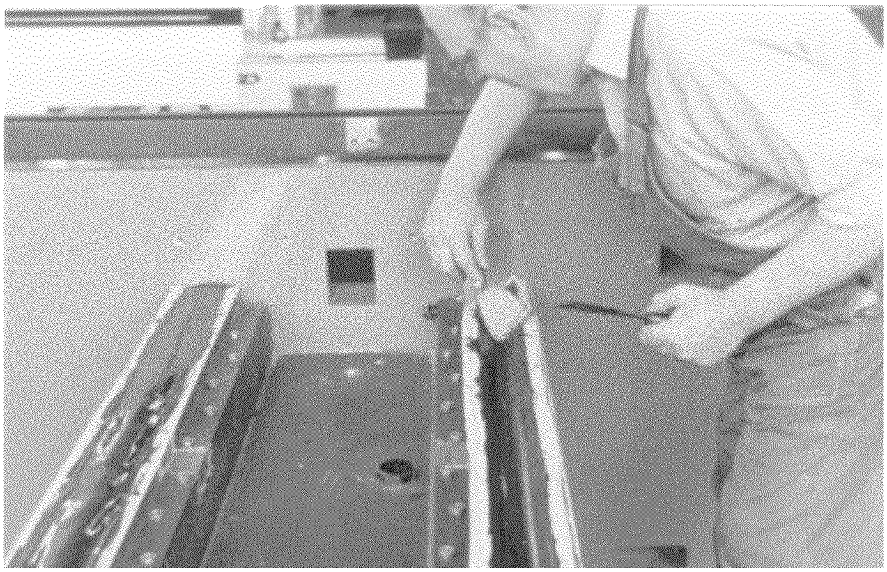


- **Aligning and defining the coating thickness for an NC-vertical turret boring machine prior to Moglicing** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).

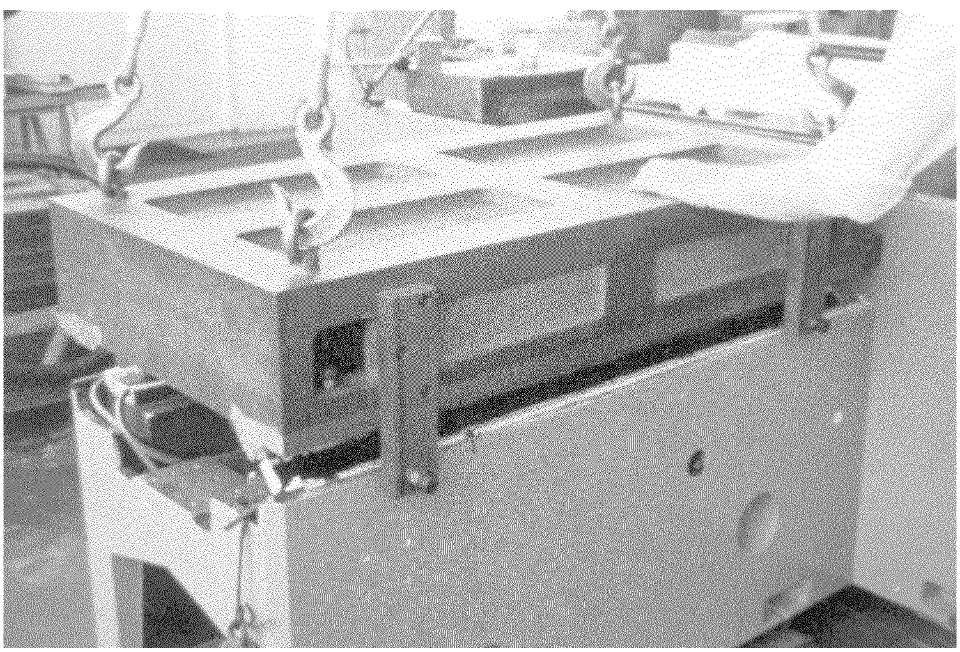
- **Guideways after Moglice™ has cured** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).



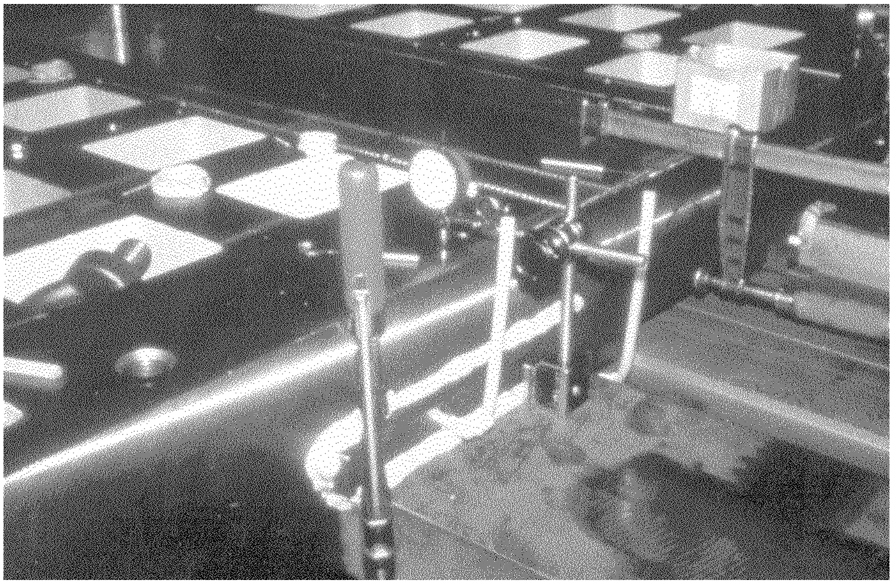
- **Moglicing guideways of an epoxy granite machine tool bed** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).



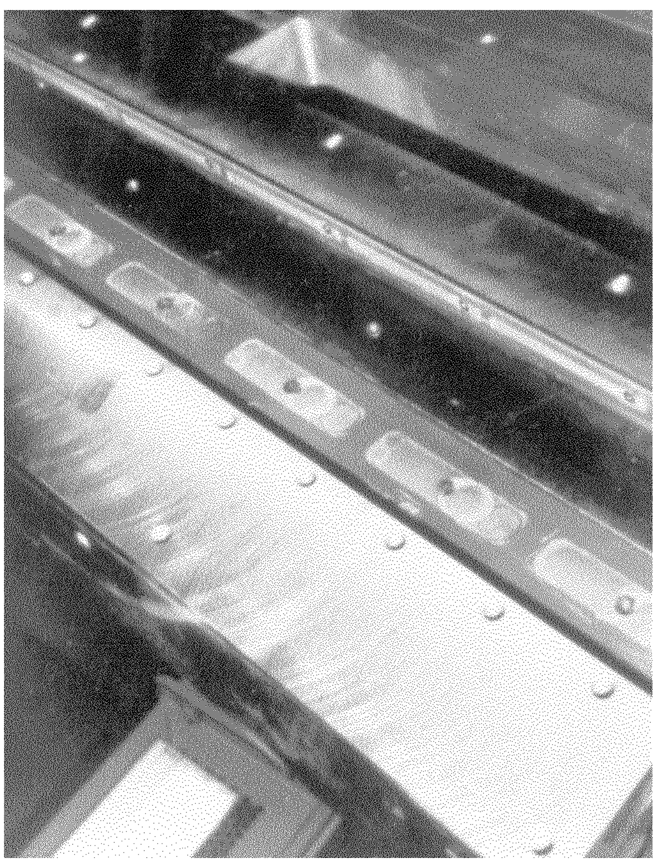
- **Molding template being put onto Mogliced guideways to achieve highly precise guideways without machining** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).



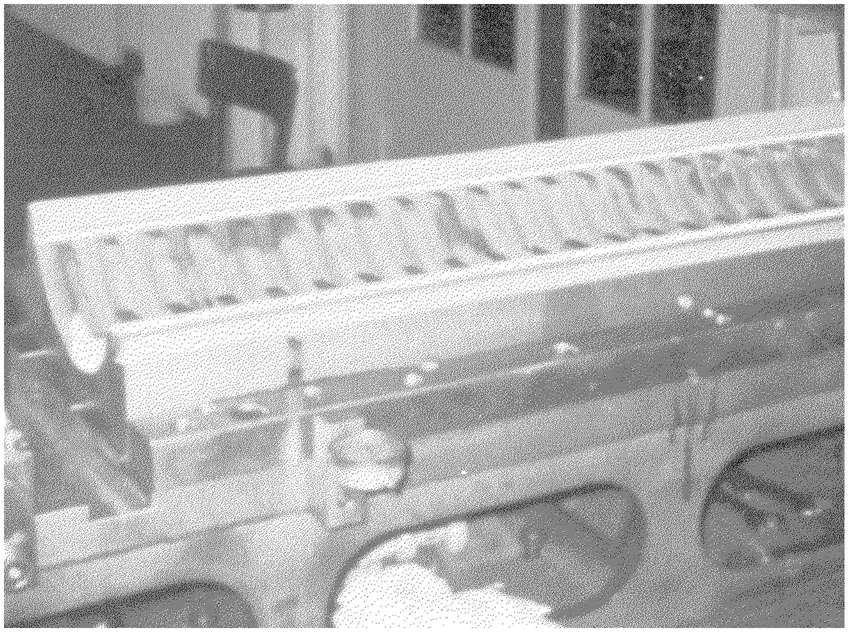
- **Risers at the head of the carriage** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).



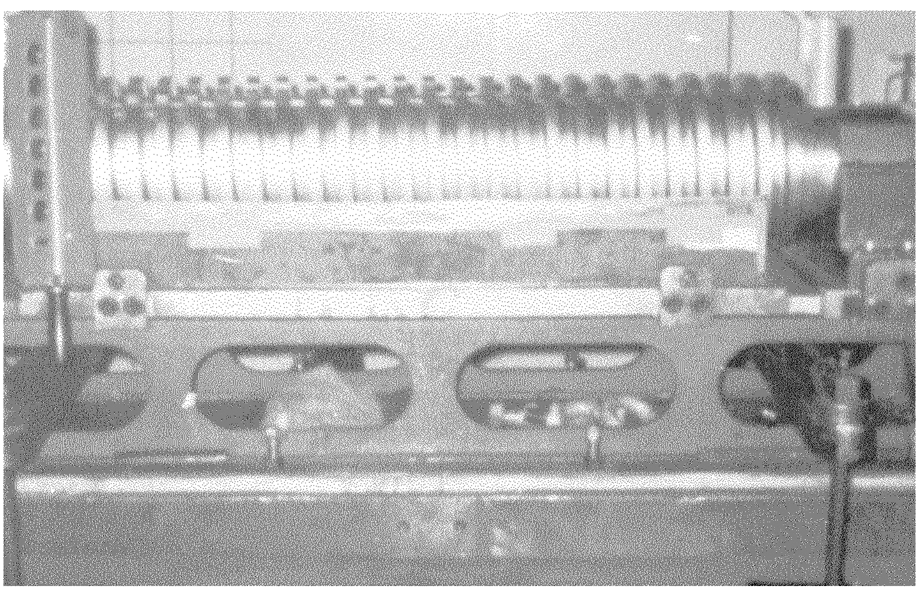
- **Mogliced guideways with molded-in hydrostatic oil pockets** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).



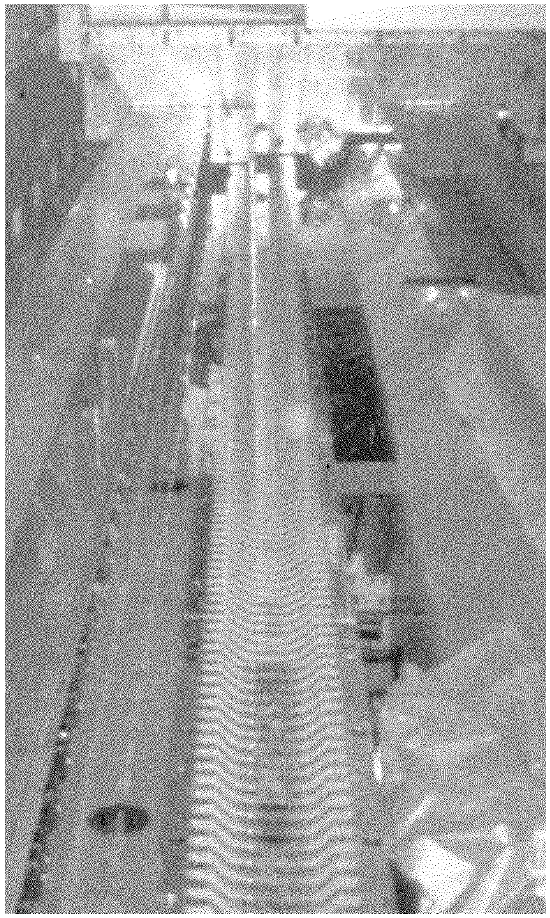
- **Coating of hydrostatic tooth racks with Moglice™ liquid type** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).



- **Released master worm aligned over the tooth rack in device** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).

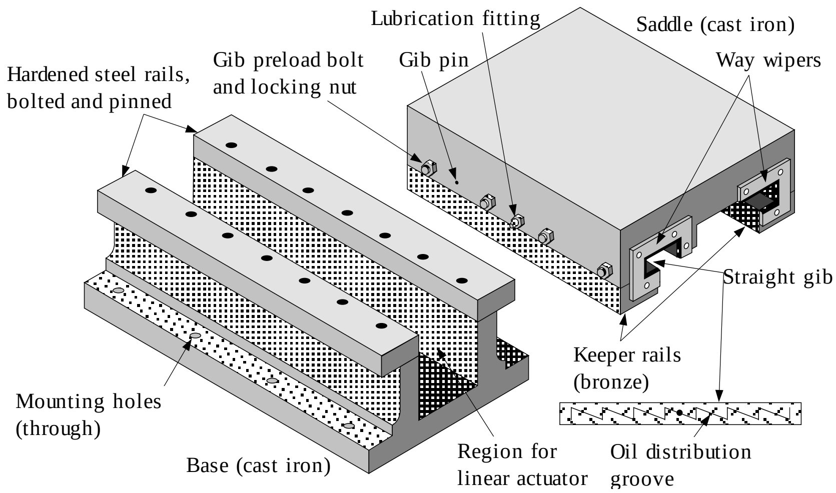


- **Rack segments assembled in a large machine** (Courtesy of Diamant-Metallplastic, GmbH & Devitt Machinery Co.).

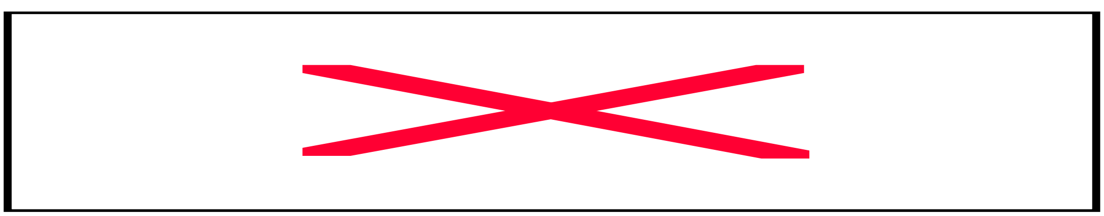


Modular rectangular (box ways) bearing assemblies

- **Components of a Tee-shaped slide. Note the straight gib and way wipers** (Courtesy of Setco Industries Inc.)**:**



- **Other possible rectangular shaped bearing designs:**

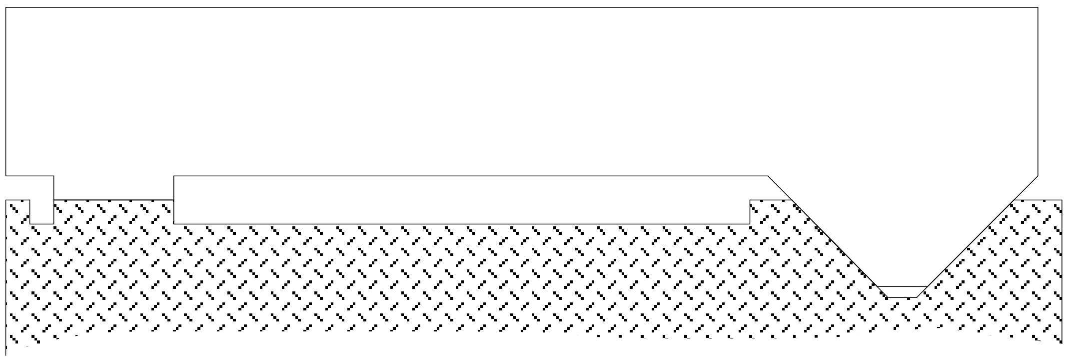


Best stance for small slides | Easiest to make | Used on larger machines

- **What are the merits of each of these designs with respect to manufacturability and performance?**
- **Which design is stiffest with respect to moments?**
    - **Remember, stiffness is proportional to width squared!**

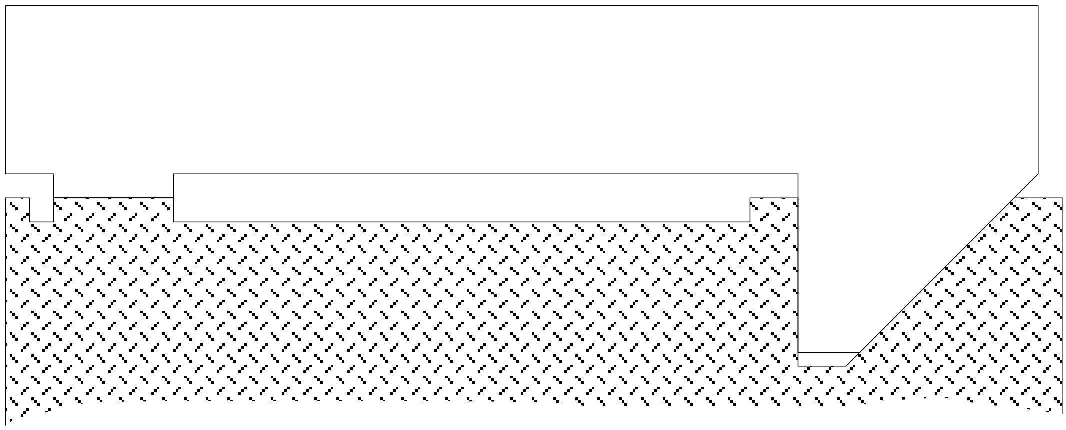
Gravity preloaded bearing configurations

- **Flat and vee:**



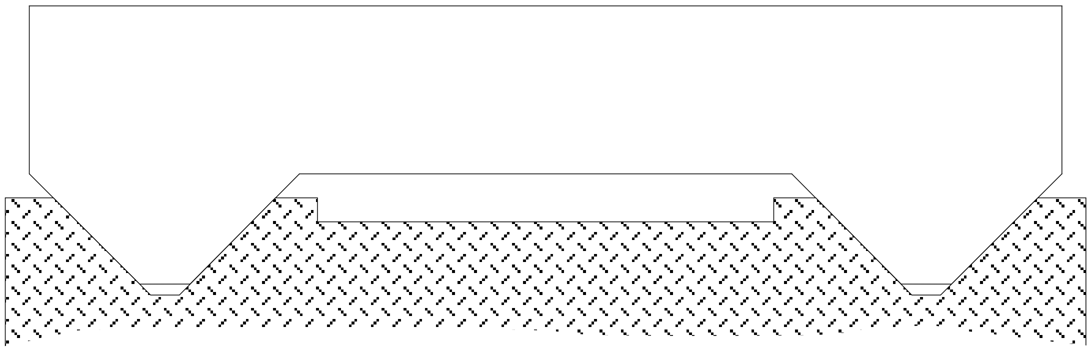
- **Easiest to manufacture.**
- **When load position changes, center-of-friction changes and yaw loads from actuator cause yaw errors.**

- **Flat and half-vee designed to resist side forces (as in a cylindrical grinder):**



- **Easy to manufacture.**
- **When load position changes, center-of-friction changes and yaw loads from actuator cause yaw errors.**
- **When subject to heavy side loads (lathe, cylindrical grinder), carriage will not lift up.**

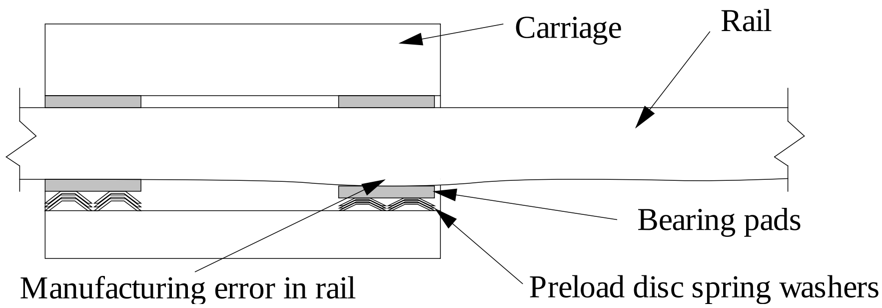
- **Double vee:**



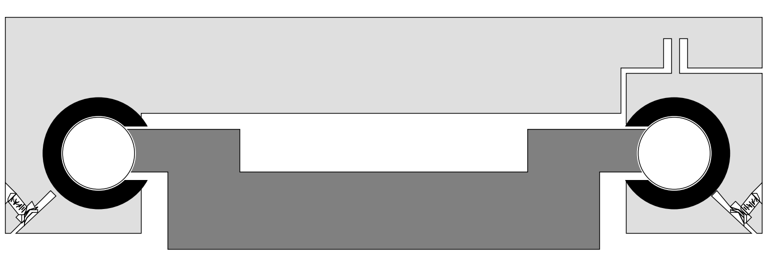
- **Difficult to manufacture.**
    - **Potentially most accurate because of self-checking form and averaging.**
- **When load position changes, center-of-friction changes only slightly and yaw loads from actuator cause minimal yaw errors.**

Bearing preload

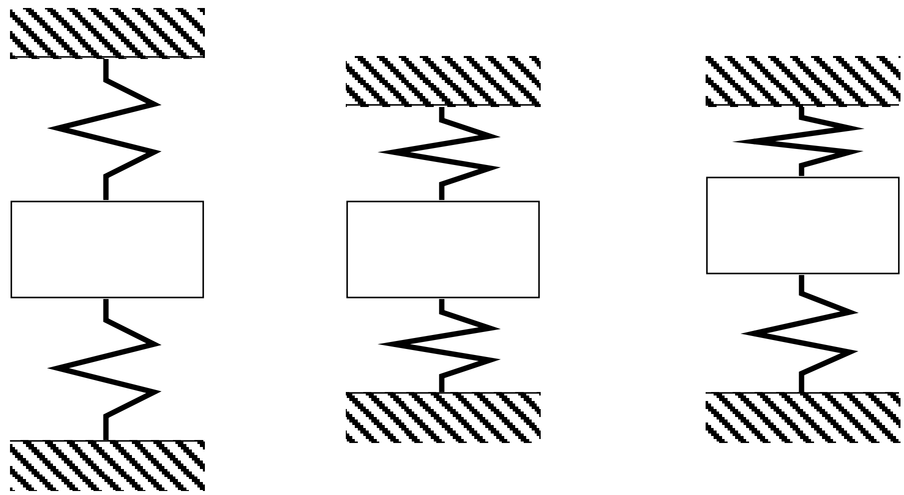
- **Allows for bi-directional loading.**
- **Can lead to overconstraint.**
- **Maximizes stiffness.**
- **Preload deflection is small, so preload can be easily lost by manufacturing errors or wear.**
- **Preload loss via wear is avoided with the use of spring loaded preload systems.**
    - **Spring loaded preload systems accommodate rail thickness variations without a large change in preload force:**



        - **If this method is to be used, the applied force cannot be greater than the preload force.**
    - **Spring loaded preload systems have limited force and moment capability.**
    - **Springs can be disk washers, or the keeper rails.**
- **Flexures can be used to allow for rail misalignment while allowing a system to be preloaded:**



- **Preload mechanics:**



No preload — Preloaded — Preloaded with force applied

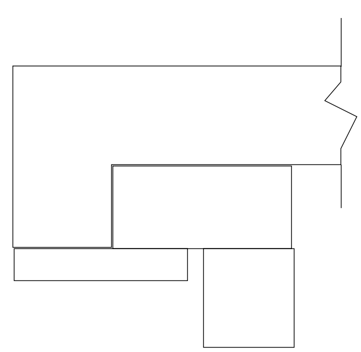
- **Sum of the forces:**

$$F_{load} - (F_{preload} + K_{upper\ pad}\,\delta) + (F_{preload} - K_{lower\ pad}\,\delta) = 0$$

- **From this and the relation $F_{load} = K_{total}\delta$:**

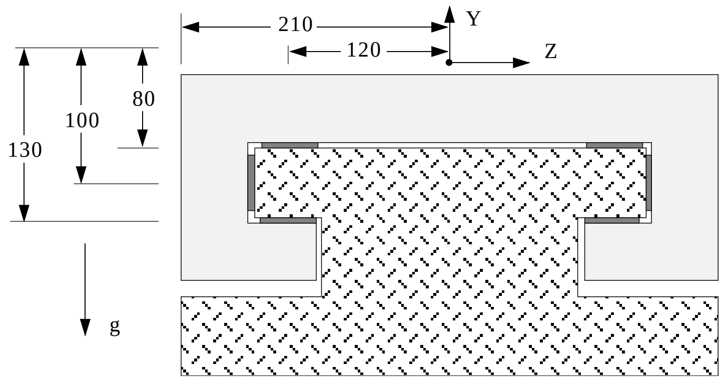
$$K_{total} = K_{upper\ pad} + K_{lower\ pad}$$

- **Careful of preload forces not being overcome by load, or stiffness falls to $K_{lower\ pad}$.**
- **Use a thin keeper rail as a light spring:**



Stiffness and load calculations: Example

- **The carriage rides on sliding contact bearings along with another identical set 480 mm into the page:**



- **Rails are ground cast iron and the bearings are DU® as received.**

- **For a 1000 N (225 lbf) preload force:**

    - **It is desired to size the bearing pads to achieve 1.75 x 10^9 N/m (10^7 lb/in) bearing stiffness.**

- **For a nominal operating point about $F_{applied} = 0$:**
  - **The stiffness will be essentially twice what either individual set of pads will be, hence:**

$$K_{pad} = \frac{K_{desired}}{2 \text{ x } 4 \text{ pad sets}} = \frac{K_{desired}}{8}$$

$$F_{pad} = \frac{F_{preload}}{4 \text{ pad sets}} = \frac{F_{preload}}{4}$$

- **For low contact pressures:**
  - **The stiffness per unit area as a function of contact pressure can be reasonably approximated by:**

$$\frac{K_{pad}}{A_{pad}} = a + \frac{bF_{pad}}{A_{pad}} + \frac{cF_{pad}^2}{A_{pad}^2}$$

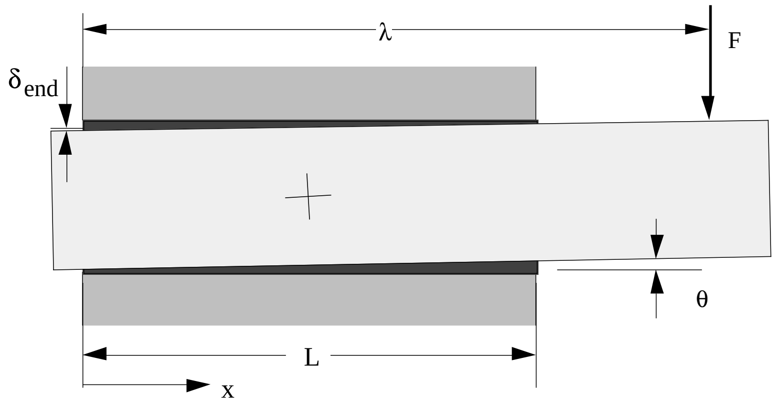
- **The coefficients a, b, and c are the product of those above and the unit conversion factor $(10^4 cm^2/m^2)*(10^6 \mu m/m)$.**

- **Solving for the bearing area yields:**

$$A_{pad} = \frac{-(bF_{pad} - K_{pad}) + \sqrt{(bF_{pad} - K_{pad})^2 - 4acF_{pad}^2}}{2a}$$

- **For the 1000 N total system preload, A_{pad} = 0.00308 m^2.**
- **The pads should be narrow to minimize keeper rail overhang.**
- **For a length to width proportion of 2:1 each pad should be about 8 cm long by 4 cm wide.**
- **Since friction is independent of area, and the bearing material is inexpensive:**
    - **Typically the entire carriage bearing surface is covered with bearing material.**
    - **Oil grooves are provided which act as lubricant reservoirs.**
    - **Decreases wear rate by lowering the surface pressure.**

- **For error budgeting, the translational and pitch stiffnesses must be defined at bearing centroid (center of stiffness).**



- **The translational stiffness of the carriage at its centroid is**

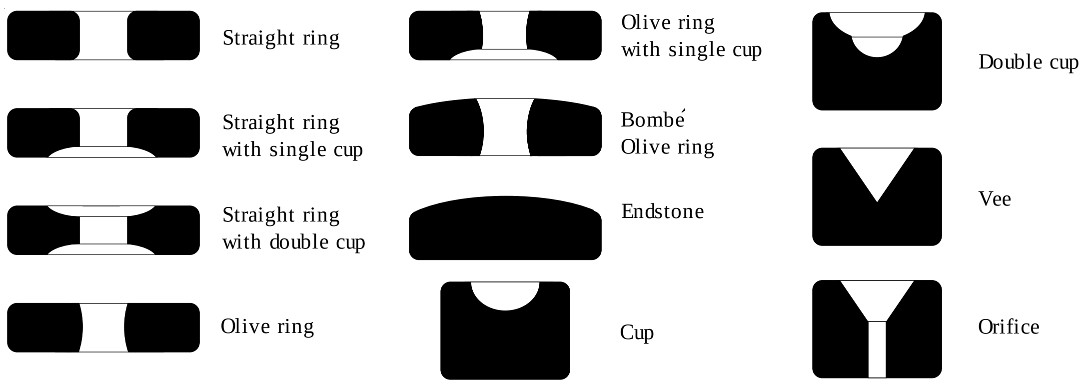
$$K_{\text{translational @ centroid}} = K$$

- **The moment applied to the carriage about its centroid is simply F(λ - L/2):**
  - **The rotational stiffness about the carriage centroid is**

$$K_{\text{rotational @ centroid}} = \frac{KL^2}{12}$$

Jewel bearings

- **Use jewels (e.g. ruby) because they are strong, stiff, wear resistant, and essentially inert.**
- **Small contact radii and low coefficient of friction with polished steel:**
    - **Make them efficient bearings for instrument applications.**
    - **Can also be used in products such as a computer mouse**
- **Standard Jewel bearing designs** (Courtesy of Swiss Jewel Co.).



- **Applications include computer mouse ball support bearings.**