Linear Motion Systems

ME EN 7960 – Precision Machine Design
Topic 3

Major Topics

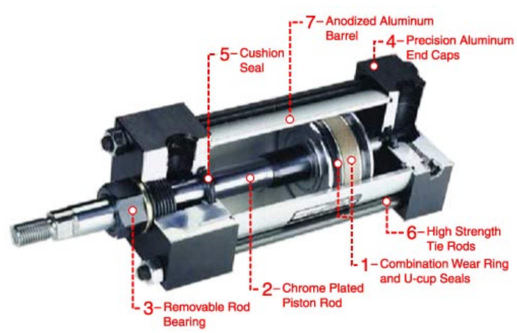
- Error sources
- Pneumatic and hydraulic cylinders
- Belt drives
- Rack and pinion drives
- Friction drives
- Lead screws
- Linear electric motors

Error Sources

- There are five principal error sources that affect linear actuator performance:
  1. Form error in the device components
  2. Component misalignment
  3. Backlash
  4. Friction
  5. Thermal effects
- These systems often have long shafts (e.g. ball screws)
  - One must be careful of bending frequencies being excited by rotating motors

Pneumatic Cylinders

- Compressed gas enters one side of the pressure chamber
- Displacement of piston occurs until force equilibrium is established
- Stick-slip occurs due to piston seals
- Gas is compressible, making motion control very difficult



Source: Milwaukee Cylinder

→ Not useful for precision motion control

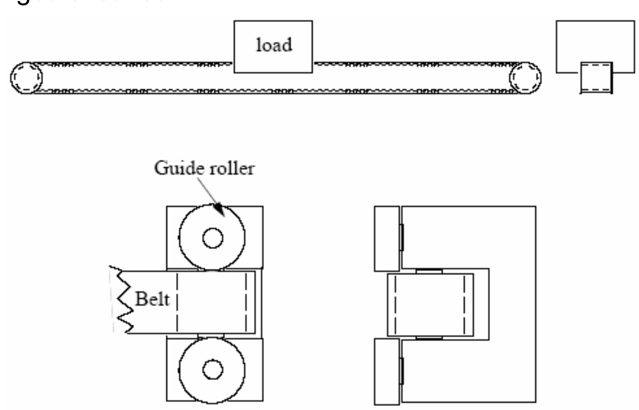
Hydraulic Cylinders

- Compressed oil enters one side of the pressure chamber
- Displacement of piston occurs until force equilibrium is established
- Stick-slip occurs due to piston seals.
- Oil is virtually incompressible, making motion control somewhat doable.

→ Not useful for precision motion control

Belt Drives

- To prevent the belts' edges wearing on pulley flanges:
  - Use side rollers to guide timing belt to prevent wear caused by flanged sheaves:



Source: Alexander Slocum, *Precision Machine Design*

Belt Drives (contd.)

- Used in printers, semiconductor automated material handling systems, robots, etc.
  - Timing belts will not slip
  - Metal belts have greater stiffness, but stress limits life

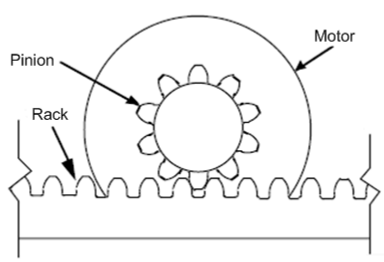
$$\sigma = \frac{Et}{2\rho}$$

E Young's modulus
t Belt thickness
ρ Bending radius

- Timing belts will be the actuator of choice for low cost, low, stiffness, low force linear motion until:
  - Linear electric motor cost comes down
  - PC based control boards with self-tuning modular algorithms become more prevalent

→ Not useful for precision motion control

Rack and Pinion Drives



Source: Alexander Slocum, *Precision Machine Design*

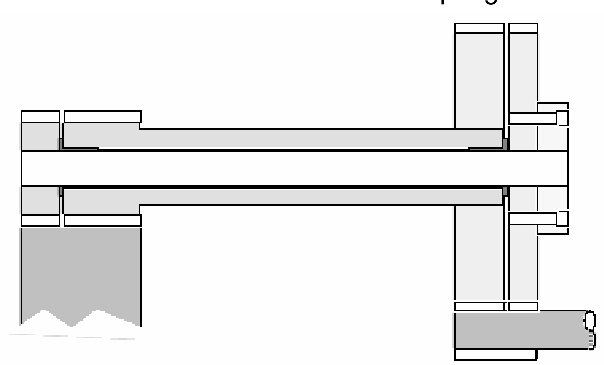
- One of the least expensive methods of generating linear motion from rotary motion
  - Racks can be placed end to end for as great a distance as long as one can provide a secure base on which to bolt them

Rack and Pinion Drives (contd.)

- Commonly used on very large machines such as gantry robots and machining centers used in the aircraft industry
- It is difficult to obtain the "optimal transmission ratio"
  - A speed reducer is sometimes used with the motor that drives the pinion
  - They do not provide a mechanical advantage the way a lead screw system does
- The characteristics of gears apply here equally well, including the use of anti-backlash or multiple pinions

Rack and Pinion Drives (contd.)

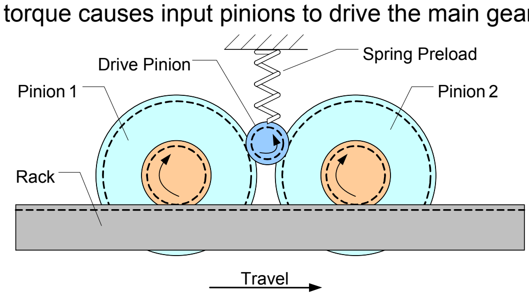
- Backlash is present in single pinion systems
- For low forces, a split preloaded pinion can be used
  - The internal tube acts as a torsional spring



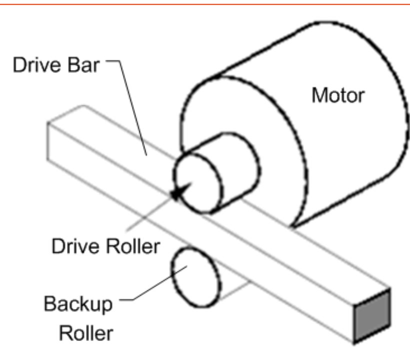
Source: Alexander Slocum, *Precision Machine Design*

Rack and Pinion Drives (contd.)

- For high force systems, a dual pinion system can be used:
  - Input shaft as a beam spring to drive two rollers:
    - Flexural force from beam spring causes input pinions to counter-rotate
    - Input pinion and motor can be mounted on cantilever beam that acts as a spring loaded pivot arm
    - Input torque causes input pinions to drive the main gear



Friction Drives



Source: Alexander Slocum, *Precision Machine Design*

- A wheel (capstan) driving a flat bar supported by a back up roller or hydrostatic flat pad bearing

Friction Drives (contd.)

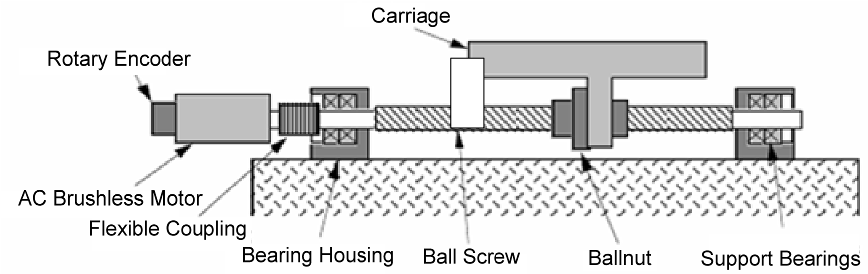
- Ideally, use hydrostatic bearings to support the drive roller shaft, and a hydrostatic flat pad bearing
- Accurate rollers are required to maintain a constant preload, transmission ratio, and constant torque
- A properly designed and manufactured friction drive can achieve nanometer resolution of motion
  - More common before linear electric motors were well developed
  - Still useful for long range of motion systems
- When a direct friction drive is properly aligned:
  - Only a pure radial bearing is needed to support the motor
  - Axial motion (walking) of the axially unrestrained shaft is an indicator of misalignment

Friction Drives (contd.)

- Friction drives' desirable properties include:
  - Minimal backlash and dead band (due to elastic deformation)
  - Low drive friction
  - Uncomplicated design
- Their undesirable properties include:
  - Low drive force capability
  - Low to moderate stiffness and damping
  - Minimal transmission gain (low motor speed makes them more susceptible to torque ripple)
  - High sensitivity to drive bar cleanliness
  - Frictional polymers can form on dry-running systems
  - As the capstan rolls, it compresses organic molecules in the air onto the drive bar which builds up a layer
    - This layer is not uniform and causes a bumpy ride and velocity control problems
  - Running the system with a tractive lubricant (e.g., Monsanto's Santotrac™):
    - Increases coefficient of friction
    - Prevents frictional polymer buildup

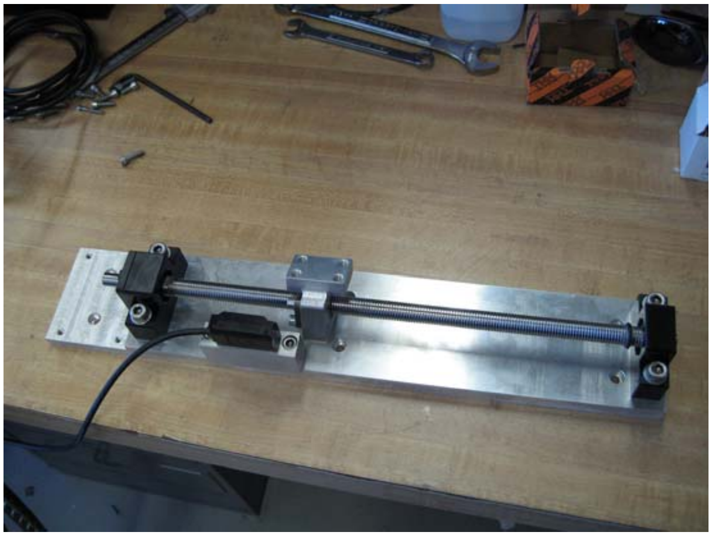
Lead Screws

- Lead screw principle has been used for centuries to convert rotary motion into linear motion with a high transmission ratio
- Modern lead screw driven servo system:



Source: Alexander Slocum, *Precision Machine Design*

Modular Ball Screw Drive System

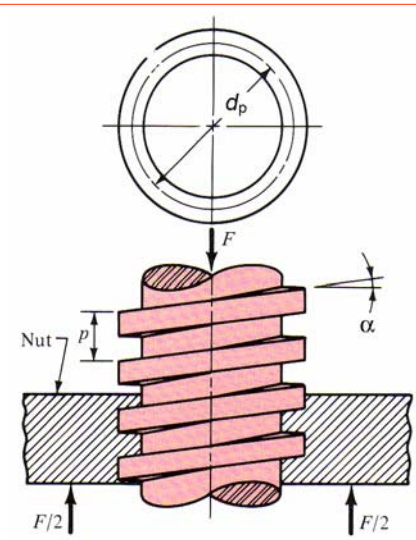


Source: Precision Design Lab

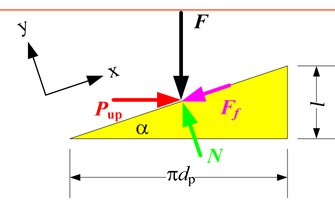
Lead Screws (contd.)

- There are many types of lead screws that are available including:
  - **Sliding contact thread lead screws**
  - Traction drive lead screws
  - Oscillatory motion lead screws
  - Non-recirculating rolling element lead screws
  - **Ball screws**
  - Planetary roller lead screws
  - Wallowing thread screws
  - Hydrostatic lead screws

The Mechanics of Power Screws - Lifting



Lifting load F



Summing up forces in x and y:

$$\sum F_x = P_{up}\cos\alpha - F\sin\alpha - F_f = 0 \quad (1)$$

$$\sum F_y = -F\cos\alpha + N - P_{up}\sin\alpha = 0 \quad (2)$$

The frictional force is found as:

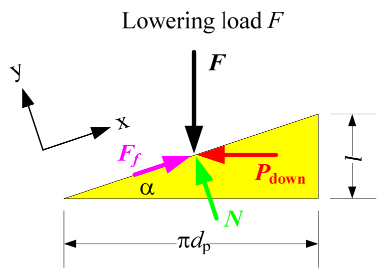
$$F_f = \mu N \quad (3)$$

(3) in (2) and in (1) and solve for P_{up}:

$$P_{up} = \frac{F(\sin\alpha + \mu\cos\alpha)}{\cos\alpha - \mu\sin\alpha} \quad (4)$$

Source: Shigley JE, Mischke CR, *Mechanical Engineering Design*

The Mechanics of Power Screws - Lowering



Summing up forces in *x* and *y*:

$$\sum F_x = -P_{down}\cos\alpha - F\sin\alpha + F_f = 0 \quad (5)$$

$$\sum F_y = -F\cos\alpha + N + P_{down}\sin\alpha = 0 \quad (6)$$

(5) in (6) and solve for P_{down}:

$$P_{down} = \frac{F(\mu\cos\alpha - \sin\alpha)}{\cos\alpha + \mu\sin\alpha} \quad (7)$$

Source: Shigley JE, Mischke CR, *Mechanical Engineering Design*

Lead Screws – Torque Calculations

Using: $$\tan\alpha = \frac{l}{\pi d_p} \quad (8)$$

(8) in (4):

$$P_{down} = \frac{F\left(\mu - \frac{l}{\pi d_p}\right)}{1 + \frac{\mu l}{\pi d_p}} \quad (9)$$

(8) in (7):

$$P_{up} = \frac{F\left(\frac{l}{\pi d_p} + \mu\right)}{1 - \frac{\mu l}{\pi d_p}} \quad (10)$$

The torque *T* applied can be written as the product of force *F* and pitch diameter d_p

$$T = \frac{Fd_p}{2} \quad (11)$$

(11) in (9):

$$T_{up} = \frac{Fd_p}{2}\left(\frac{l + \pi\mu d_p}{\pi d_p - \mu l}\right) \quad (12)$$

(11) in (10):

$$T_{down} = \frac{Fd_p}{2}\left(\frac{\pi\mu d_p - l}{\pi d_p + \mu l}\right) \quad (13)$$

Source: Shigley JE, Mischke CR, *Mechanical Engineering Design*

Lead Screws – Torque Calculations (contd.)

For the case of an **Acme** screw, the wedging effect of the thread angle needs to be considered. This is done by dividing the frictional terms in Eq. (12) and (13) by *cos*θ.

$$T_{up} = \frac{Fd_p}{2}\left(\frac{l\cos\theta + \pi\mu d_p}{\pi d_p\cos\theta - \mu l}\right) \quad (14) \qquad T_{down} = \frac{Fd_p}{2}\left(\frac{\pi\mu d_p - l\cos\theta}{\pi d_p\cos\theta + \mu l}\right) \quad (15)$$

Source: Shigley JE, Mischke CR, *Mechanical Engineering Design*

Self Locking

Screws are said to be self-locking if the friction inside the nut is large enough to create a positive torque. Self-locking resists spinning of the nut when an external force *F* is applied to the threaded shaft.

Thus the condition for self-locking is:

$$\pi\mu d_p > l\cos\theta \quad (19)$$

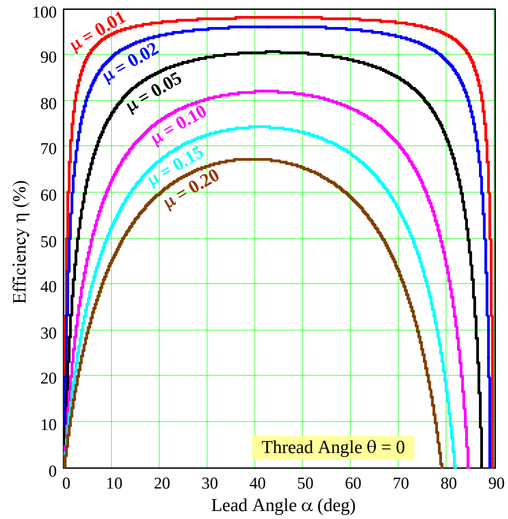
Lead Screws (contd.)

- The efficiency η is:

$$\eta = \frac{\cos\theta - \mu\tan\alpha}{\cos\theta + \mu\cot\alpha} \quad (17)$$

For square thread:

$$\eta = \frac{1-\mu\tan\alpha}{1+\mu\cot\alpha} \quad (18)$$



Source: Juvinall RC, Marshek KM, *Fundamentals of Machine Component Design*

Stresses in Lead Screws

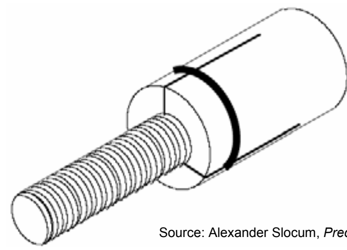
- The force that is generated creates tensile and torsional shear stresses
- The thread root is a stress concentration area (a factor of 2-3), which is somewhat mitigated when the threads are rolled (as opposed to cut)
- Assuming a thread root diameter r_{tr} , the stresses are:

$$\sigma_{tensile} = \frac{F_{tensile}}{\pi r_{tr}^2} \qquad \tau_{shear} = \frac{2T}{\pi r_{tr}^3}$$

The equivalent (Von Mises) stress:

$$\sigma_{equivalent} = \sqrt{\sigma_{tensile}^2 + 3\tau_{shear}^2}$$

Sliding Contact Lead Screws



Source: Alexander Slocum, *Precision Machine Design*

- Molded plastic nuts are often split and preloaded by an O-ring which puts circumferential pressure on the nut
- Commercially available thread ground and lapped sliding contact thread lead screw assemblies may have nuts preloaded against each other
- They may have split nuts that are preloaded with a circumferential spring

Sliding Contact Lead Screws (contd.)

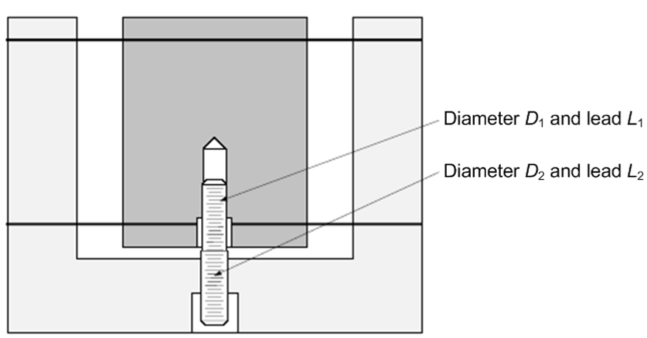
- Range from least expensive (machine finished) to most expensive (lapped) lead screws.
- Usually the nut is made of a bearing brass or bronze but can also be made from PTFE or the nut can be replicated.
- For low force applications, the nut can be bored without threads and then have axial slits cut into it.
  - The nut is then placed over a fine pitch lead screw (e.g. 100 threads per inch).
  - O-rings circumferentially clamp the nut and the screw will then make its own impressions into the nut.

Sliding Contact Lead Screws (contd.)

- The coefficient of friction between a sliding thread contact lead screw can range from:
  - 0.1 for a greased nut
  - 0.05 for a lightly loaded lapped thread
- Load capacity is an order of magnitude less than for a ball screw
- However, the lapped continuous contact thread provides much greater smoothness of motion
- Allows a ground and lapped screw to achieve sub-micro-inch motion once initial stick slip has been overcome
- Sliding contact threads can also be replicated in-place, and sometimes can even be used to make a hybrid screw

Differential Lead Screws

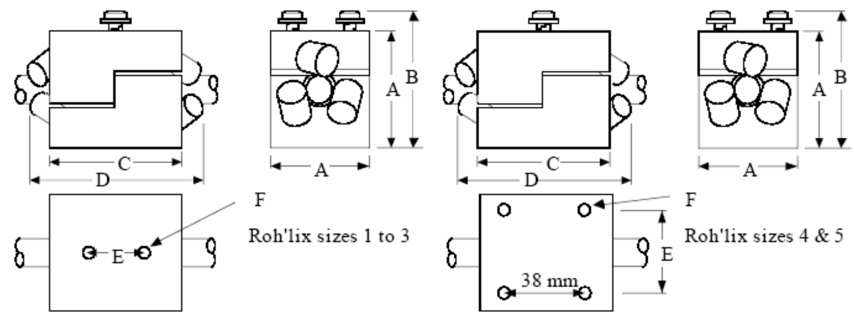
- For very large transmission ratio if lead L_1 and lead L_2 have same hand
- For very small transmission ratio if lead L_1 and lead L_2 have opposite hand



Source: Alexander Slocum, *Precision Machine Design*

Traction Drive Lead Screw

- Cam roller-type traction drive lead screw (Courtesy of Zero-Max a unit of Barry Wright):



Source: Alexander Slocum, *Precision Machine Design*

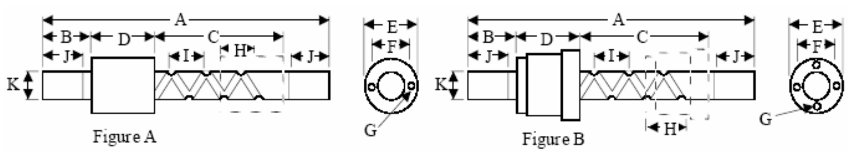
- The cam rollers' axes are inclined to the axis of the shaft
  - The angle of inclination determines the lead

Traction Drive Lead Screw (contd.)

- The efficiency of this type of screw is generally on the order of 0.9 (90%) and load capacity is low
- If overloaded, the nut will slip
  - For a CMM that uses linear encoders for accuracy, the slip capability is ideal from a crash/safety perspective
- For applications requiring moderate accuracy and load capability with high efficiency and low cost
  - The shaft is smooth and round so it is exceptionally easy to seal
- Beware of the buildup of frictional polymers on the shaft!

Oscillatory Motion Lead Screws

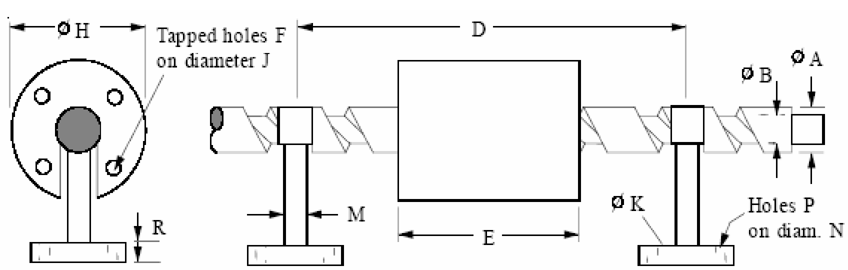
- For applications requiring linear oscillatory motion over a fixed path
- Various turnaround curve profiles are available which allows the dwell to be chosen for the application
- A typical application would be in photocopying machines
- Characteristics of a lead screw that provides oscillating motion (Courtesy of Norco Inc.):



Source: Alexander Slocum, *Precision Machine Design*

Non-Recirculating Rolling Element Lead Screws

- Metric Rollnuts for very long range of motion actuation (Courtesy of Norco Inc.):



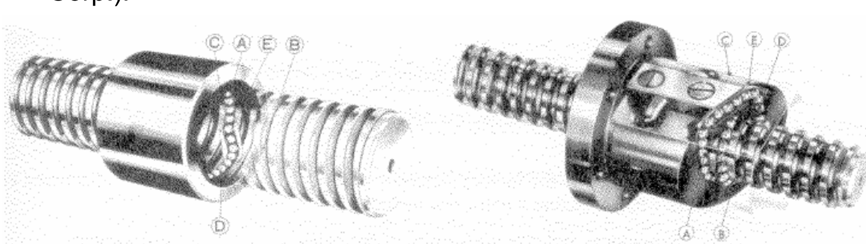
Source: Alexander Slocum, *Precision Machine Design*

Non-Recirculating Rolling Element Lead Screws (contd.)

- Primary feature of the Rollnut is the rolling elements are fixed and can pass over discontinuities in the shaft
- A very long shaft can be spliced together and suspended by shaft hangers
- The non-rotating nut can travel tens of meters without worry of shaft deflection and critical speeds except for regions between hangers
- Very useful in material handling systems

Ball Screws

- There are two main types of ball screw nuts (Courtesy of NSK Corp.):



- The tube-type uses a pick-up finger to gather the balls as they exit the nut's thread helix and a tube to direct them back to the beginning of the thread helix.
  - Large lead/diameter ratios are possible (2:1)
  - The speed of the shaft (rpm) x shaft diameter (mm) is limited to about 90,000

Source: Alexander Slocum, *Precision Machine Design*

Ball Screws (contd.)

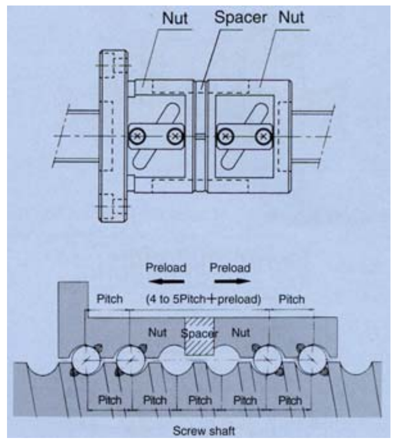
- Ball screws are perhaps the most common type used in industrial machinery and precision machines
- Ball screws can be used to easily achieve repeatability on the order of one micron
- Specially manufactured and tested ball screws can attain submicron motion resolution
- Very high efficiency is obtained by using rolling steel balls to transfer loads from the screw shaft to the nut threads
  - Smaller spacer balls in-between load-carrying balls increases the allowable speed and the smoothness of operation (greater resolution)
  - The use of spacer balls halves the number of load carrying balls, so load capacity is cut by roughly 50%

Preloading Methods

- Preloading removes backlash in ball screw nuts
- There are four basic ways:
  - Tensile preloading is created by inserting an oversize spacer between two nuts and then clamping the nuts together
  - Compressive preloading uses an undersize spacer between two nuts that are clamped together
  - P-type preloading uses oversize balls, and a single nut to reduce cost
  - Z-type preloading is also obtained with a single nut by shifting the lead between ball circuits
- Preloading reduces the load capacity, increases the nut stiffness, and increases internal friction (heat!!!)

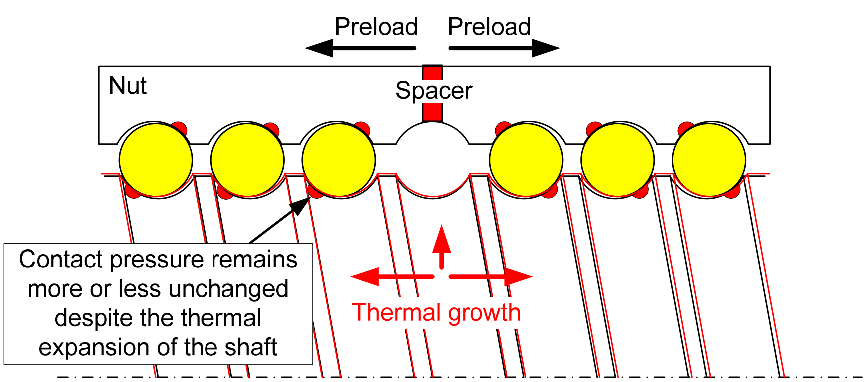
Tensile Preloading

- Tensile preloading is created by inserting an oversize spacer between two nuts and then clamping the nuts together:
  - One nut takes loads in one direction and the other takes loads in the other direction
  - This creates a back-to-back mounting effect that is thermally stable for a rotating shaft design
  - Just like for rotary ball bearings, a back-to-back nut is more sensitive to misalignment errors



Source: THK Co., Ltd.

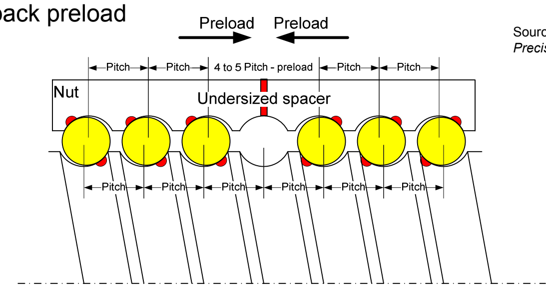
Tensile Preloading – Thermal Stability



Scenario: Temperature of the shaft is greater than that of the nut. Because the contact pressure remains largely unchanged despite the thermal expansion of the shaft, the system is called *thermally stable*.

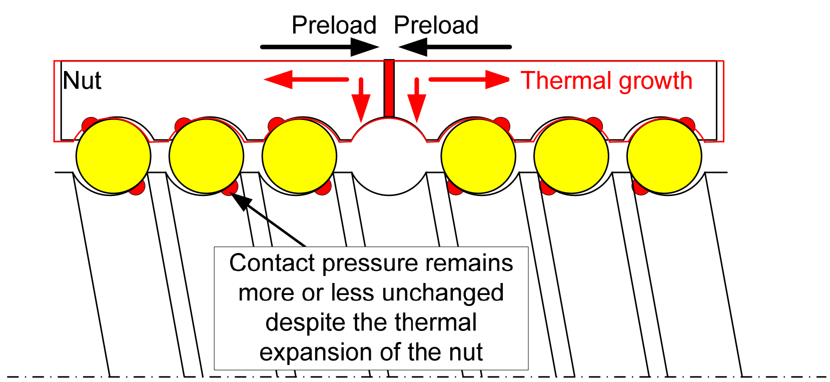
Compressive Preloading

- Compressive preloading uses an undersize spacer between two nuts.
  - This creates a face-to-face mounting situation:
    - Thermally stable if the nut is likely to be hotter than the lead screw
  - If the nut has an angular displacement imposed on it due to mounting errors:
    - The ball loads will be lower and life will be longer than with a back-to-back preload



Source: Alexander Slocum, *Precision Machine Design*

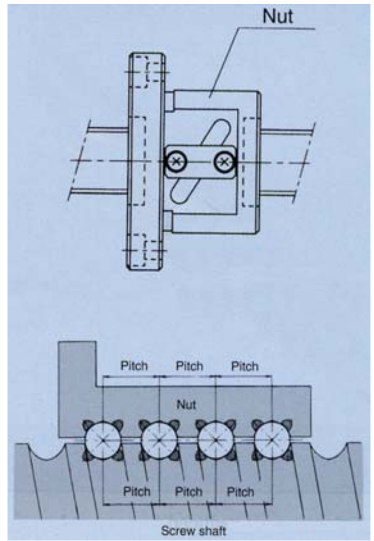
Compressive Preloading – Thermal Stability



Scenario: Temperature of the nut is greater than that of the shaft. Because the contact pressure remains largely unchanged despite the thermal expansion of the nut, the system is called *thermally stable*.

P-Type Preloading

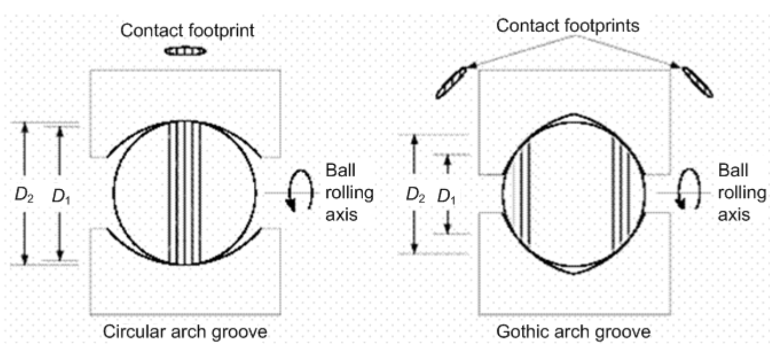
- P-type preloading uses oversize balls, and a single nut to reduce cost
- Preload is obtained by four point contact between the balls and the Gothic arch thread shape of the shaft and the nut
  - This greatly increases the amount of skidding (differential spin) the ball is subjected to
  - Because of skidding, this type of preload should not be used for precision systems
    - If an axis is primarily loaded in one direction (gravity), the P-type preloading is effective and economical



Source: THK Co., Ltd.

P-Type Preloading (contd.)

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

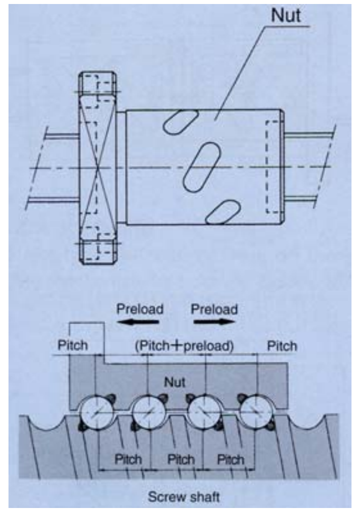


Source: Alexander Slocum, *Precision Machine Design*

- As sensitive to misalignment as is tensile preloading

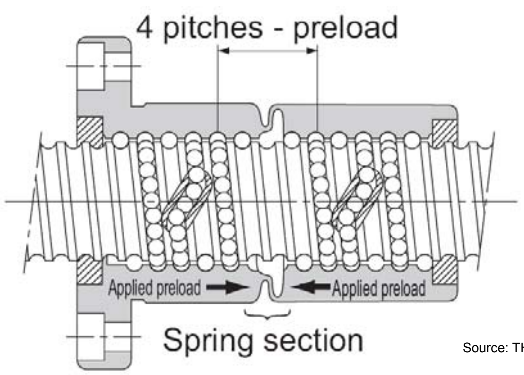
Z-Type Preloading

- Z-type preloading is also obtained with a single nut by shifting the lead between ball circuits
  - This creates two point contact between the balls and the grooves
  - Tensile or compressive mode
  - Two types:
    - Two circuits with spaced lead
    - Single circuit with the circuit having a midway transition point or "skip" by the preload amount
  - No differential spin occurs, hence high degree of accuracy for an extended period of time



Source: THK Co., Ltd.

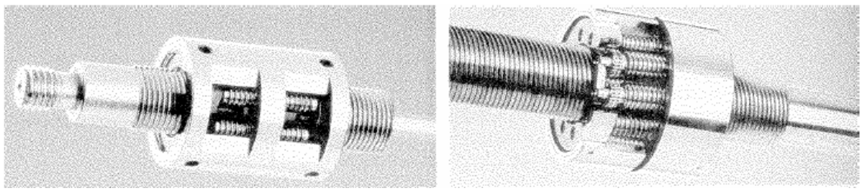
Spring Type Preload



Source: THK Co., Ltd.

- Simple preload method
- Thermally stable
- Useful if stiffness is not required

Roller Screws



Source: Alexander Slocum, *Precision Machine Design*

- Use rollers instead of balls to convert rotary to linear motion and transfer forces between the nut and the shaft
- Rollers have a single thread with a pitch equal to the lead screw's apparent pitch (real pitch / number of leads)
- The rollers mesh with both the screw and the nut

Recirculating Roller Screws

- The nut has a region that allows the rollers to move radially out of the shaft thread
- A cam sends the rollers back to start a new circuit
- Allows for very fine pitch threads (2 mm)

Some Facts about Roller Screws

- Roller screw size ranges:
  - Diameter ranging from 3.5 to 200 mm
  - Pitch ranging from 1 to 40 mm
  - Single nut dynamic load capacity ranging from 5300 N to 753 kN
- The nut can be made in one piece without preload, or in two pieces if preload is required
- Maximum speed of a planetary roller lead screw is ω (rpm) x D (mm) = 140,000 (twice that of a ball screw)
- The large number of contacting threads creates a large averaging effect
- This also gives roller screws load and stiffness capabilities many times higher than similar diameter ball screws

Some Facts about Roller Screws (contd.)

- Depending on the screw, a roller screw may cost one to three times as much as a ball screw
  - Hertz contact area is 3x that of a same size ball screw
  - Load capacity is 3x that of a same size ball screw
  - Life = $(F/Fmax)^3$, so life is 27x that of a same size ball screw
- Roller screws are manufactured with accuracies and efficiencies equal to those of ball screws
  - CAREFUL: Tens-of-hours run-in may be required to ensure the very stiff nuts are properly preloaded!
- Planetary roller screws are much more quiet than ball screws