Precision Machine Design

Topic 21

Linear motion actuators

Purpose:

This lecture provides an introduction to the design issues associated with linear power transmission elements.

Major topics:

- **Error sources**
- **Belt drives**
- **Rack and pinion drives**
- **Friction drives**
- **Leadscrews**
- **Linear electric motors**

"...screw your courage to the sticking-place,

And we'll not fail"

Shakespeare

Error sources:

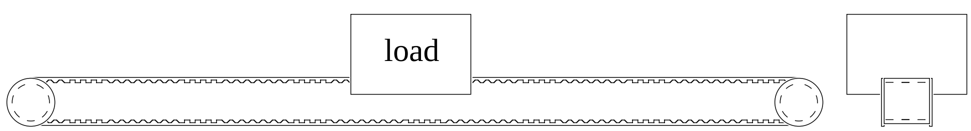
- **There are five principal error sources that affect linear actuator' performance:**
    - **Form error in the device components.**
    - **Component misalignment.**
    - **Backlash.**
    - **Friction.**
    - **Thermal effects**
- **These systems often have long shafts (e.g., ballscrews).**
   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

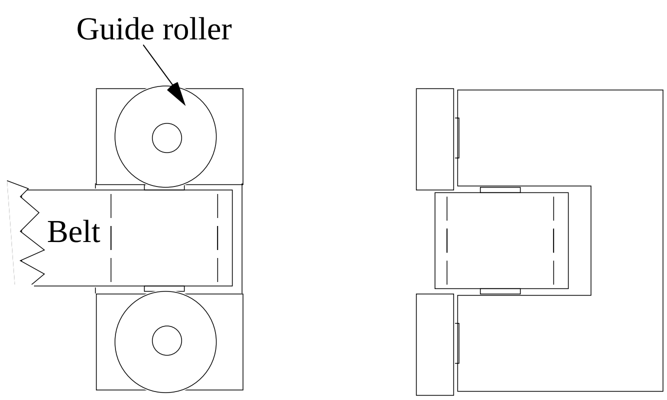
Belt drives

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

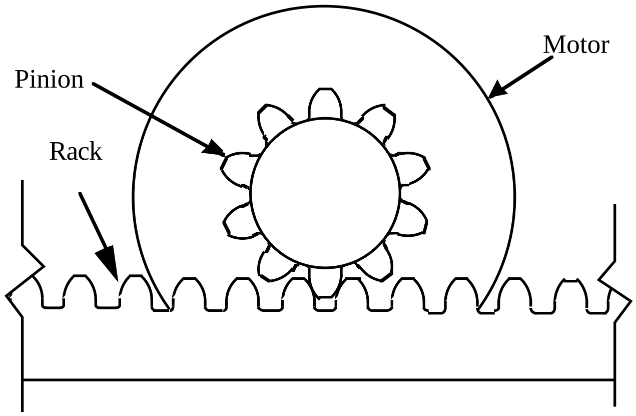
$$\sigma = \frac{Et}{2\rho}$$

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



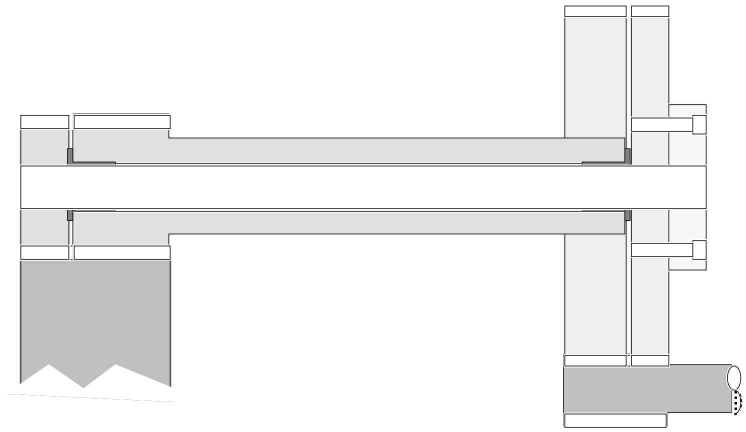


Rack and pinion drives

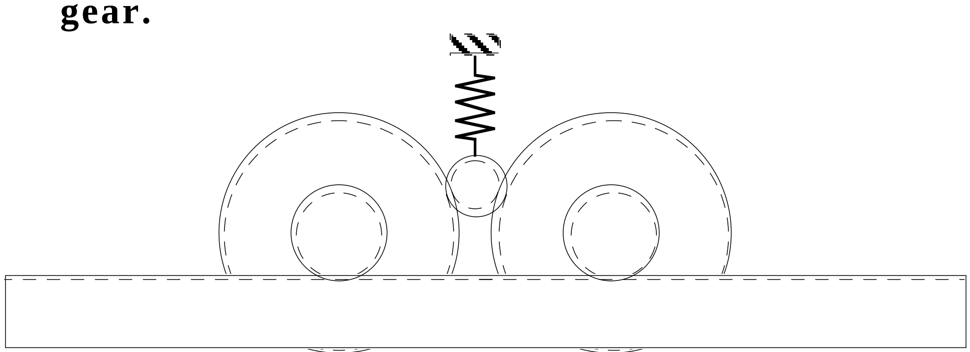


- One of the least expensive methods of generating linear motion from rotary motion.
    - Racks can be placed end to end for as great a distance as one can provide a secure base on which to bolt them.
- Commonly used on very large machines such as gantry robots and machining centers used in the aircraft 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 leadscrew system does.
- The characteristics of gears apply here equally well, including the use of antibacklash or multiple pinions.

- **Backlash is present in single pinion systems.**
- **For low forces, a split preloaded pinion can be used:**



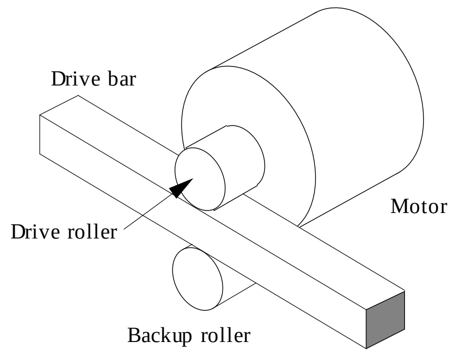
  - **The internal tube acts as a torsional spring.**
- **For high force systems, a dual pinion system can be used:**
  - **Input shaft as a beam spring to drive two rollers:**
    - **Flexural force from beam spring causes input pinions to counter-rotate.**
    - **Input pinion and motor can be mounted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



- **A hydrostatic linear worm drive (Johnson drive) can be used for a zero-backlash, zero static friction system:**
  - **Generally used on very large machine tools, but hydrostatic racks are very messy.**

Friction drives

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



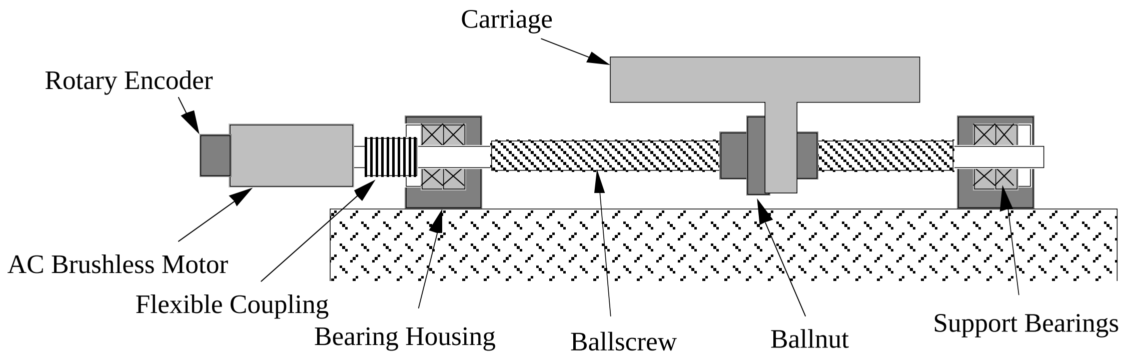
- Ideally, use fluidstatic bearings to support the drive roller shaft, and a fluidstatic flat pad bearing.
- Accurate rollers are required to maintain a constant preload, transmission ratio, and tare torque.
- A properly designed and manufactured friction drive can achieve nanometer resolution of motion.
  - More common before linear electric motors were well developed.
  - Still useful for long range of motion systems (intrabay cleanroon material handling systems)
- When a direct drive 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 alignment.

- **Friction drives' desirable properties include:**
  - **Minimal backlash and deadband (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 susceptable 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.**

Leadscrews

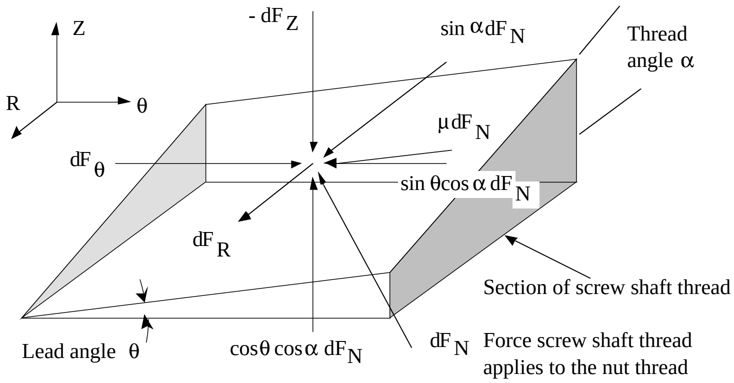
- **Leadscrew principle has been used for centuries to convert rotary motion into linear motion with a high transmission ratio.**

- **Modern leadscrew driven servo system:**



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

- **The amount of force a screw can generate, given friction in the threads, is determinable from basic physics of the force generated by a wedge[1]:**



Where:

- **Γ is the applied torque**
- **μ is the coefficient of friction**
- **r is the pitch radius of the screw thread**
- **p is the lead of the thread (e.g., inches/rev)**
- **R is the thrust bearing radius**
- **α is the thread angle**
- **β is 2R/p**

- **To raise a load, the torque required is:**

$$\Gamma_{required} = F_{desired}\left(\left(\frac{2\pi\mu r + p\cos\alpha}{2\pi r\cos\alpha - \mu p}\right)r + R\mu\right)$$

[1] For a REALLY thorough examination of this subject, including off-axis moments created by the applied torque, see A. Slocum Precision Machine Design, published by SME, Dearborn, MI.

- **To lower a load F, the torque required is:**

$$\Gamma_{required} = F_{desired}\left(\left(\frac{2\pi\mu r - p\cos\alpha}{2\pi r\cos\alpha + \mu p}\right)r + R\mu\right)$$

- **The screw will not back-drive when:**

$$p < \frac{2\pi r\mu}{\cos\alpha}$$

- **The efficiency η is:**

$$\eta = \frac{\cos\alpha(\pi\beta\cos\alpha - \mu)}{\pi\beta\cos\alpha(\cos\alpha + \pi\beta\mu)}$$

The torque applied to the threaded shaft creates stresses

- **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:**

$$\sigma_{tensile} = \frac{F_{Tensile}}{\pi r_{tr}^2}$$

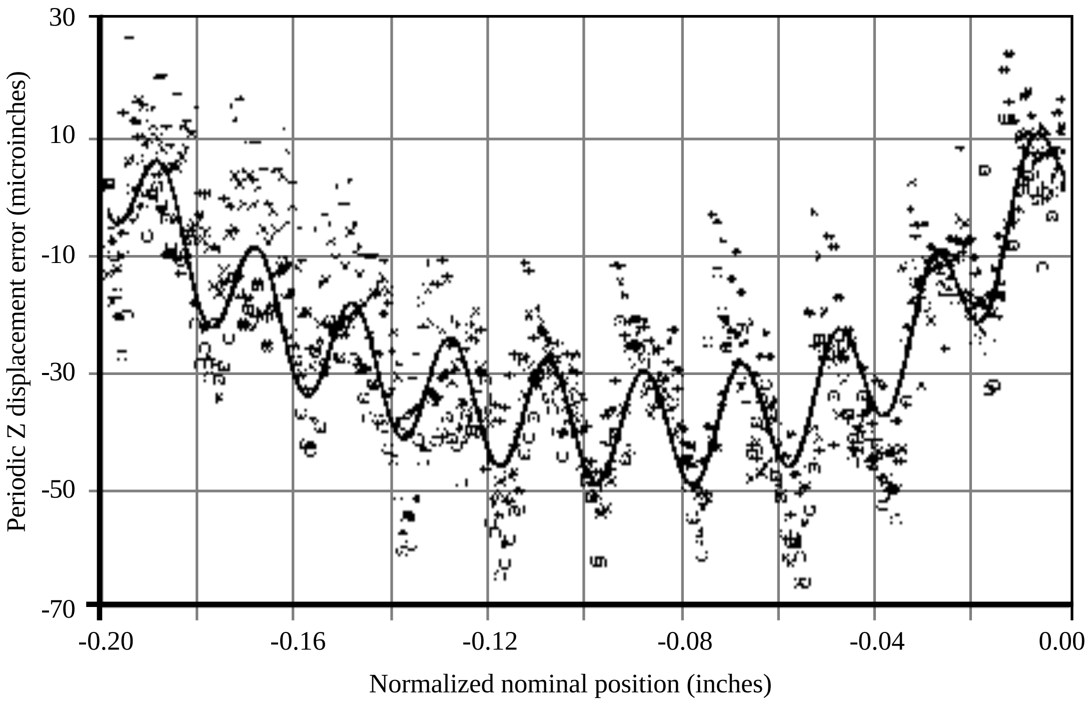
$$\tau_{shear} = \frac{2\Gamma r_{tr}}{\pi r_{tr}^4}$$

The equivelent (Von Mises) stress is:

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

Error sources:

- **Nothing is perfect: Periodic Z displacement error for one ballscrew revolution:**

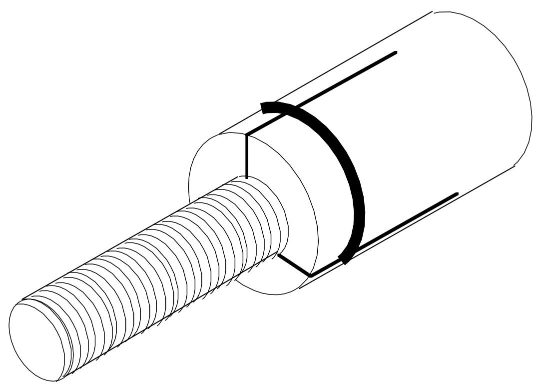


- **Leadscrews (including ballscrews) may be subject to many different types of error sources including.**
    - **Lack of squareness between the thrust collar and the thrust bearing (periodic errors).**
    - **Journal support bearing errors (periodic errors, lateral motion, and backlash).**
    - **Support journal and screw shaft eccentricity (periodic errors, and carriage straightness errors).**
    - **Lateral and angular misalignment between the screw and carriage (carriage straightness errors).**
    - **Leadscrew shaft straightness (carriage straightness errors).**
    - **Varying pitch diameter (periodic error and backlash).**
    - **Mating thread form profile errors (periodic errors, backlash, and limits resolution).**
    - **Thread form errors (drunkenness) (periodic errors).**
    - **Recirculating elements (sources of noise and error).**
    - **When generating an axial force, a leadscrew also generates moments about axes orthogonal to the shaft.**

- **Periodic errors can usually be readily mapped or obviated through the use of linear position sensors.**
- **Resolution can be increased by polishing components.**
- **To minimize backlash:**
    - **Use two nuts that are preloaded against each other.**
    - **Use oversize rolling elements**
    - **Use a split-circumferentially clamped nut.**
- **For ballscrews, avoid four-point contact preloads (which generate significant ball-slip) when extreme precision is required.**
- **For ballscrews for low-load high precision applications, specify spacer balls and experiment with the return tubes' position.**
    - **The return tube on top uses gravity to help load the balls into the return path and increases smoothness.**
- ***Caveat Emptor!***

Sliding contact thread leadscrews

- **Range from least expensive (machine finished) to most expensive (lapped) leadscrews.**
- **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 leadscrew (e.g. 100 threads per inch).**
  - **O rings circumferentially clamp the nut and the screw will then make its own impressions into the nut.**

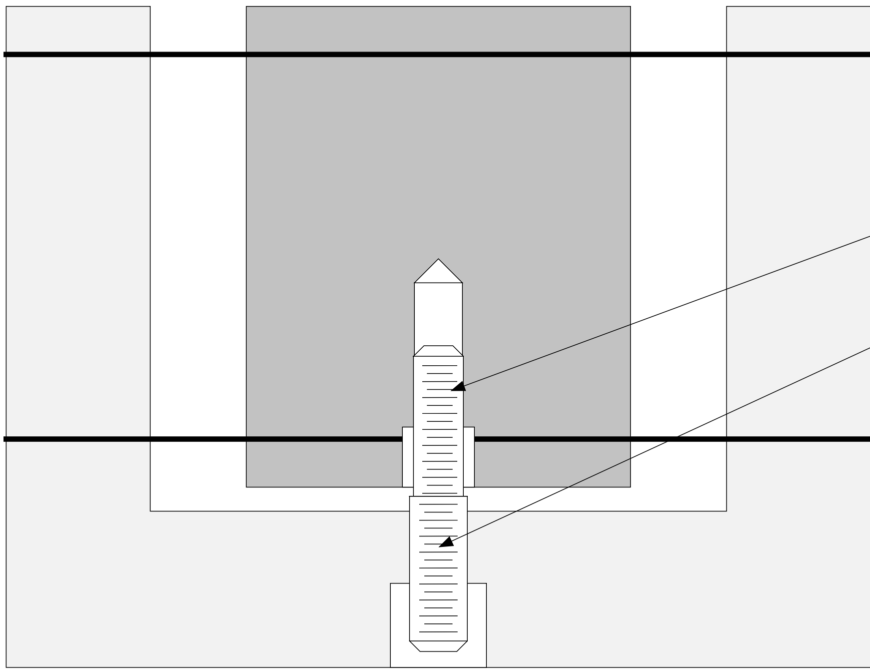


- **Molded plastic nuts are often split and preloaded by an O ring which puts circumferential pressure on the nut.**

- **Commercially available thread ground and lapped sliding contact thread leadscrew assemblies may have nuts preloaded against each other.**
- **They may have split nuts that are preloaded with a circumferential spring.**
- **The coefficient of friction between a sliding thread contact leadscrew 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 ballscrew.**
- **However, the lapped continuous contact thread provides much greater smoothness of motion.**
    - **Allows a ground and lapped screw to achieve sub-microinch 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 leadscrews

- **Used to obtain a very high transmission ratio:**

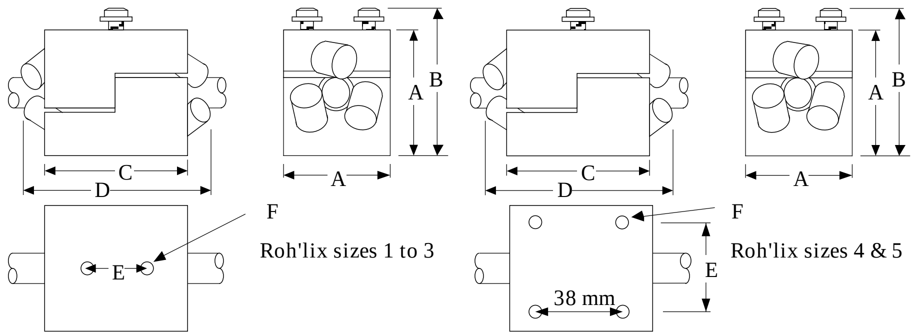


Example:

Inch series				
D1	0.438	Screw size 7/8-14		
L1	0.0714			
D2	0.500			
L2	0.0769	Screw size 1/2-13		
Leffective	0.0055			
Metric series				
D1	8.000	Screw size M8x1.25		
L1	1.2500			
D2	10.000	Screw size M10x1.5		
L2	1.5000			
Leffective	0.2500			

Traction drive leadscrews

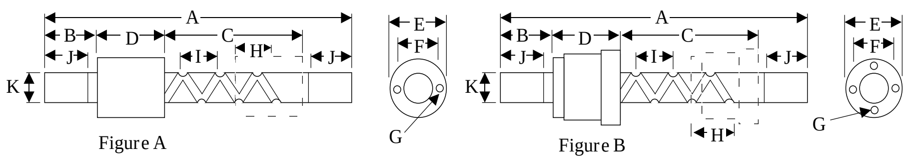
- **Cam roller-type traction drive leadscrew** (Courtesy of Zero-Max a unit of Barry Wright)**:**



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

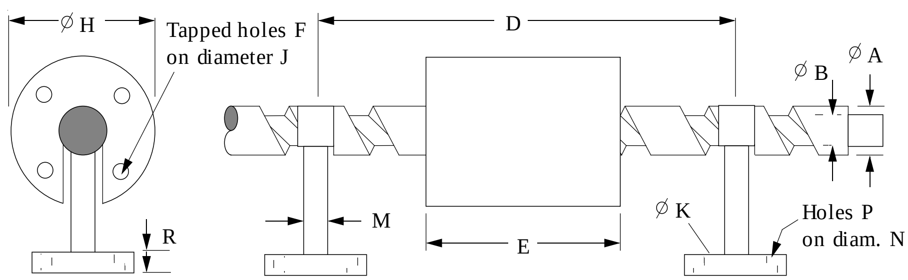
- **For applications requiring linear oscillatory motion over a fixed path.**
- **Various turnaround curve profiles are available which allows the dwell to be chosen for the application.**
- **A typical application would be in photocopying machines.**
- **Characteristics of a leadscrew that provides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



	1600 (Fig A)	1700 (Fig A)	1800 (Fig A)	1900 (Fig B)	2000 (Fig B)	2100 (Fig B)
K	9.53	12.7	19.05	31.75	44.45	63.50
I	12.70	19.05	25.40	31.75	50.80	76.20
B	38.10	50.80	99.06	154.94	198.12	198.12
J	-	-	108.70	152.40	177.80	203.20
D	35.05	47.50	65.02	104.90	127.00	171.45
E	24.89	30.99	41.15	60.20	82.55	113.54
H	18.80	25.40	34.04	57.66	64.77	89.41
F	19.81	23.88	33.27	49.28	68.33	95.25
G	M3	M4	M6	M8	M8	M12
$A_{min.}$	122	166	291	438	578	644
$A_{max.}$	427	623	900	1200	1797	2473
$C_{min.}$	11.2	16.6	22.3	28.5	44.5	63.5
$C_{max.}$	316	474	632	791	1264	1892
$F_{max.}$	53	98	173 or 434	534 or 1254	1068 or 2638	1899 or 4893

Non-recirculating rolling element leadscrews

- **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 of tens of meters without worry of shaft deflection and critical speeds except for regions between hangers.**
- **Very useful in material handling systems.**
- **Metric Rollnuts for very long range of motion actuation** (Courtesy of Norco Inc.)**:**



Model	A	B	l_{Min}	l_{Max}	l_{std}	D	K	L	M	N	P	R	E	F	H	J	Dyn load	Static load
25L06	25	17.1	10	40	25	1000	50	55	12.7	35	7	6	205	M6	70	60	2000	3000
38L11	38	26.2	20	50	35	1200	80	70	20	60	9	12	292	M8	102	88	6000	9000
50L14	50	35.3	25	80	50	1500	80	90	20	60	9	15	350	M10	130	110	10000	15000
75L19	75	55.8	40	110	75	2000	90	120	25	70	12	15	505	M12	180	150	20000	30000

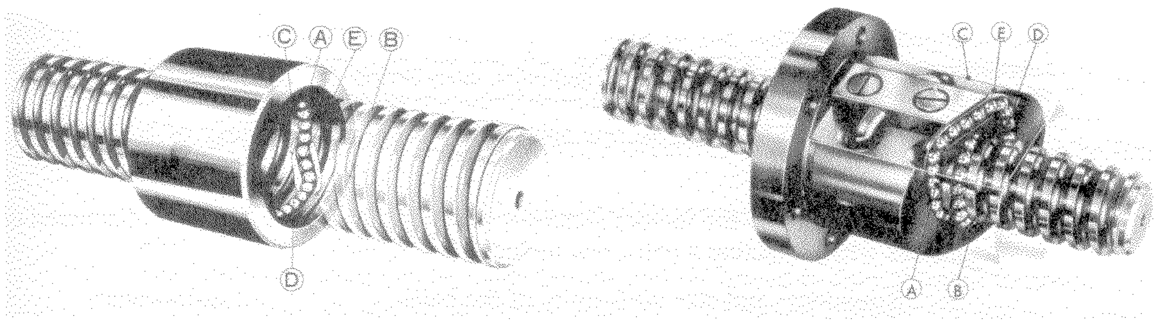
Units are mm and Newtons

Ballscrews

- **Ballscrews are perhaps the most common type of leadscrew used in industrial machinery and precision machines.**
- **Ballscrews can be used to easily achieve repeatability on the order of one micron.**
- **Specially manufactured and tested ballscrews can attain submicroinch 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 decreases.**
- **No rolling element is perfect and under load balls lose their sphericity.**
- **Even ballscrews have finite efficiencies as was shown earlier.**

Nut design

- **There are two main types of ballscrew 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.**
- **An internal crossover-type ball deflector-type performs the same operation internally but without a small finger.**
    - **Modest lead/diameter ratios are possible (1:1)**
    - **The speed of the shaft (rpm) x shaft diameter (mm) is limited to about 70,000.**
        - **Special proprietary designs can increase this by a factor of 2.**
    - **Internal ball deflectors can only be used on ballscrews with small to moderate leads.**
    - **They make for a quieter ballscrew that is more easily mounted.**

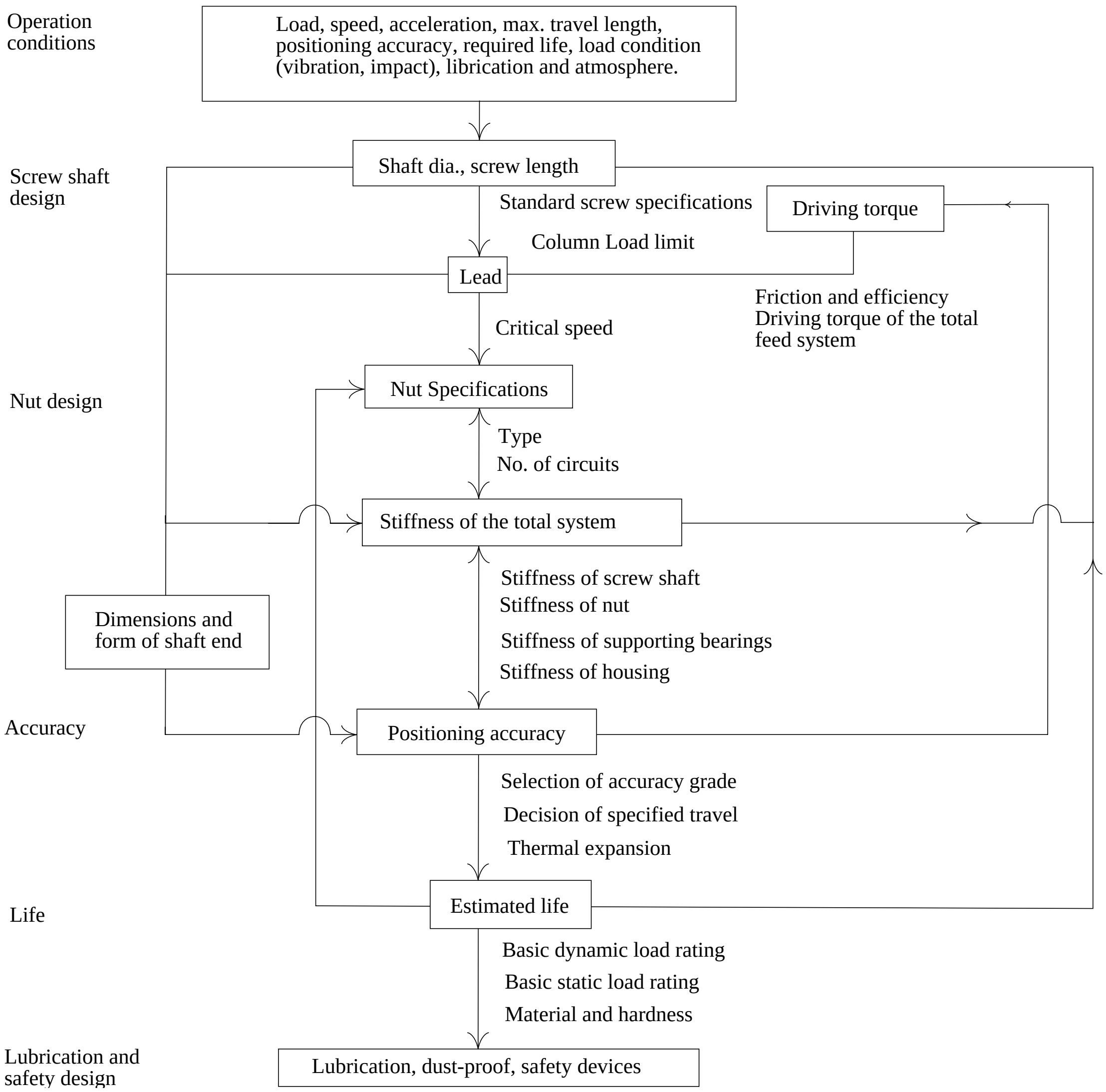
- **Ballscrew applications** (Courtesy of NSK Corp.)**:**

	C0	C1	C2	C3	C5	C7	C10
Boring machine			•	•	•		
CMMs	•	•	•				
Drilling machine				•	•	•	
EDM		•	•	•	•		
Grinding machine	•	•	•	•			
Jig borer	•	•					
Lathe	•	•	•	•	•		
Laser cutting machine				•	•		
Milling machine		•	•	•	•		
Machining center	•	•	•	•	•		
Punching press				•	•		
Robots:							
Cartesian-assembly		•	•	•	•		
Cartesian-material handling					•	•	•
Revolute-assembly		•	•	•	•		
Revolute-material handling				•	•	•	
Semiconductor equipment							
Insertion machine			•	•	•	•	
PCB driller		•	•	•	•	•	
Prober	•	•	•				
Steppers	•	•					
Wire bonder		•	•				
Wood working machines					•	•	•

- **The accuracy class descriptors (e.g. C0, C1, etc.) are particular to the manufacturer.**

- **The values are typical for precision ballscrew manufacturers.**

- **Ballscrew selection procedure** (Courtesy of NSK Corp.)**:**



- **The selection procedure is straightforward and can be used for the selection of other types of leadscrews as well.**

- **Many ballscrew manufacturers have computer programs to help guide the design engineer in selecting the proper ballscrew.**

Ballscrew accuracy

- **In addition to the factors generally affecting leadscrew accuracy discussed earlier:**
- **Factors to consider when selecting a ballscrew include:**
    - **Roundness and size uniformity of the balls.**
    - **Design of the recirculating entrance and exit paths.**
    - **Mechanical compensation for thermal expansion.**
    - **Lead accuracy.**
    - **Preload.**
    - **Mounting accuracy.**
- **In general, because balls can be made so well so easily, problems lie in the thread and not the balls.**
- **Engineers used to rely on a precision ballscrew to allow them to use an encoder or resolver to determine linear position.**
    - **Now resolution and zero backlash are most often sought, because linear encoders are often used.**
    - **For systems with high friction (i.e. some sliding contact bearings):**
        - **A rotary sensor on a ballscrew can help to minimize jerk when the servo starts from a standstill.**
        - **Hence lead accuracy is of prime concern in some applications.**

- **As the balls leave the thread on their way to be recirculated, they can either leave suddenly or gradually roll out.**
    - **The former condition leads to a noisy ballscrew with a roughness of motion.**
    - **A ballscrew manufacturer concerned with precision will carefully taper the entrance and exit paths.**
- **Even when the entrance and exit paths are tapered:**
    - **The balls compressing and decompressing contributes to the audible noise of a fast moving ballscrew.**
    - **This creates axial disturbance forces that can typically be seen on the sub-micron level.**

- **Ballscrews have less than perfect efficiency:**

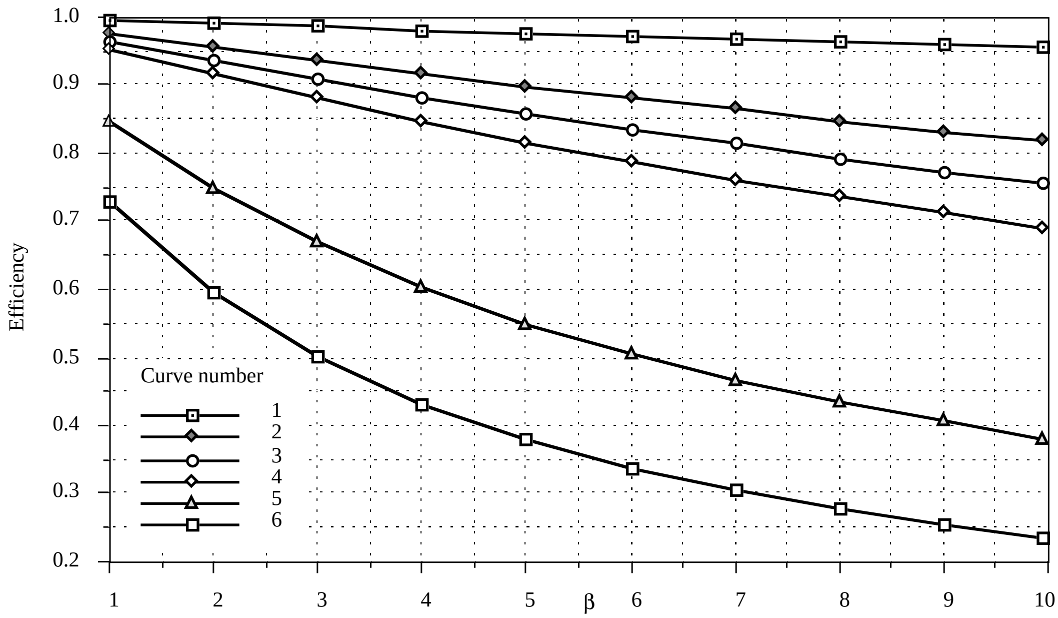
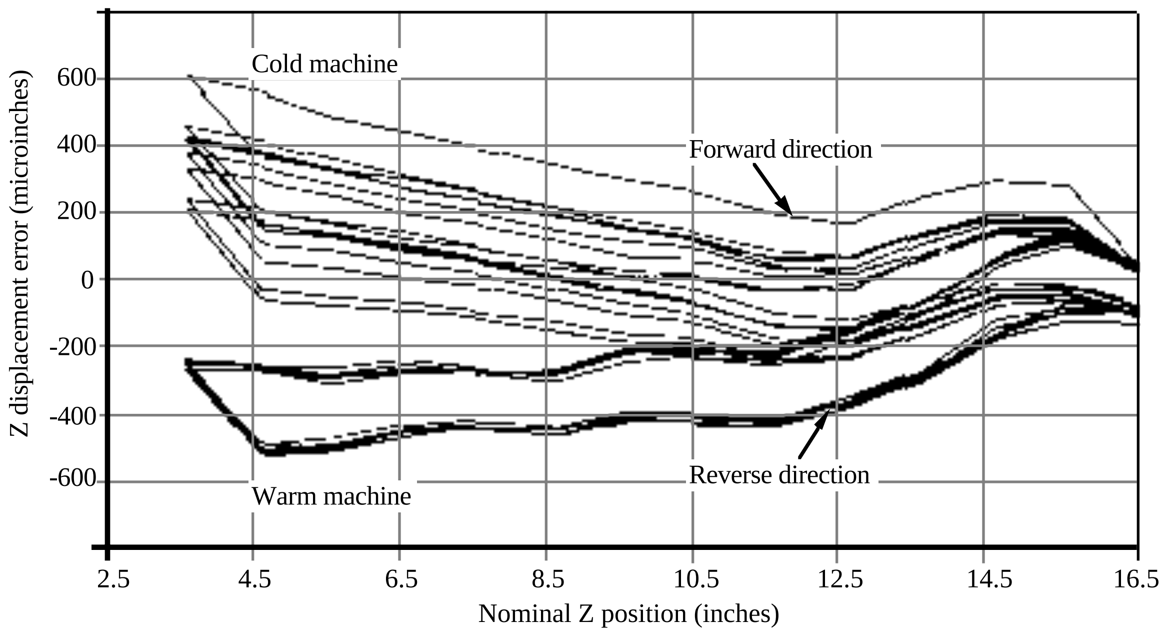


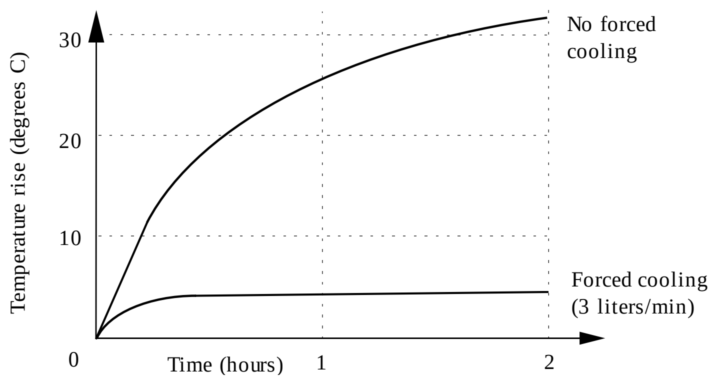
Figure 10.8.8 Leadscrew efficiency: (1) light preload special finish ballscrew $\alpha = 45^o$ and $\mu = 0.001$, (2) light preload ballscrew $\alpha = 45^o$ and $\mu = 0.005$, (3) lubricated lapped lightly loaded Acme thread $\alpha = 14.5^o$ and $\mu = 0.01$, (4) heavy preload ballscrew $\alpha = 45^o$ and $\mu = 0.01$, (5) lubricated ground Acme thread $\alpha = 14.5^o$ and $\mu = 0.05$, (6) lubricated tapped Acme thread $\alpha = 14.5^o$ and $\mu = 0.1$.

- **The support bearings and ballnut can generate considerable heat in fast moving high cycle machines.**
  - **Thermal drift in a ballscrew driven sliding contact bearing supported axis:**



- **Heat transfer out of the screw is difficult since the screw is only held by point contacts to the rest of the machine.**
- **As the screw expands, an error in lead can result which can be compensated for:**
  - **The screw can be made with a deliberate negative lead error. A lead offset may be from 20-50 μm/m.**
  - **The screw can be pretensioned in its bearing mounts which stretches the lead until the screw thermally expands.**
    - **The increased load on support bearings generates considerable heat and wears them faster.**

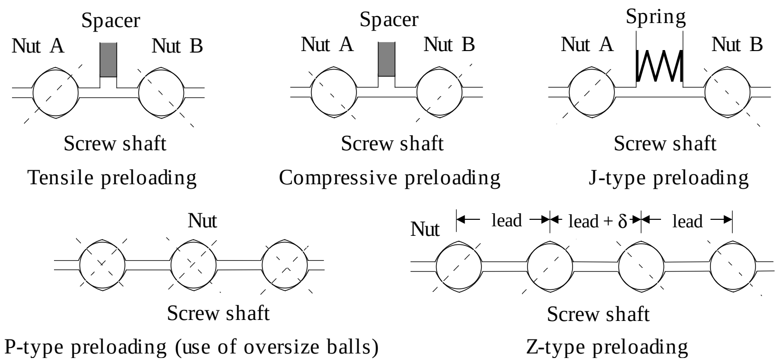
- **The ballscrew shaft can be made hollow and oil forced to flow through it producing a cooling effect, OR**
    - **Use a larger lead which increases efficiency and decreases rotation speed.**
    - **Monitor temperature and make software based error corrections.**
    - **Use a linear position sensor (e.g. linear encoder) for closed loop control.**
- **Effect of forced cooling of a hollow ball screw with 32 mm shaft diameter, 10 mm lead, and 1500N preload** (After Sato at Makino Milling Machine Corp.)**:**



- **Oil forced through the nut and journal support bearings:**
    - **Increases lubrication.**
    - **Decreases wear and noise.**
    - **Removes heat from a sensitive part of the machine.**
- **However this requires an oil distribution, collection, and temperature control system.**
- **Unless the oil is carefully kept separate from cutting fluid:**
    - **It should be used only as a coolant and not forced through the nut.**

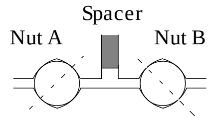
Preloading methods

- **Ballnut preload methods** (Courtesy of NSK Corp.)**:**



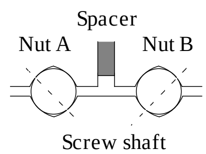
Class of preload	Operating conditions	Application examples
Heavy Medium	Vibration and shock loads Overhanging or offset loads Heavy cutting forces	Machining center, turning center
Medium Light	Light vibration Light overhanging or offset loads Light and medium cutting loads	Surface grinder, jig grinder, robots, laser processing machine, PCB drilling machine
Light	Slight vibration	XY table for semiconductor mfg.
Very light	No overhanging or offset loads Light and precise operation	CMM tables, high-speed machines, EDM machines
Very light Clearance	Machines with large amounts of thermal growth High accuracy is not required	Welding machines, automatic tool changers, material handling equipment

- **Design and manufacturing quality can be assesed by oscillating the nut.**
  - **Non-optimal ballscrews' balls will bunch up and jam the return path.**
  - **A good ballscrew will not lock up after severe oscillation.**



Tensile preloading

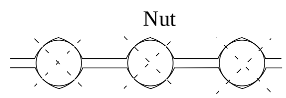
- **Tensile preloading is created by inserting an oversize spacer between two nuts and then clamping the nuts together:**
    - **One nut takes loads in one direction and the other takes loads in the other direction.**
    - **This creates a back-to-back mounting effect that is thermally stable for a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



Compressive preloading

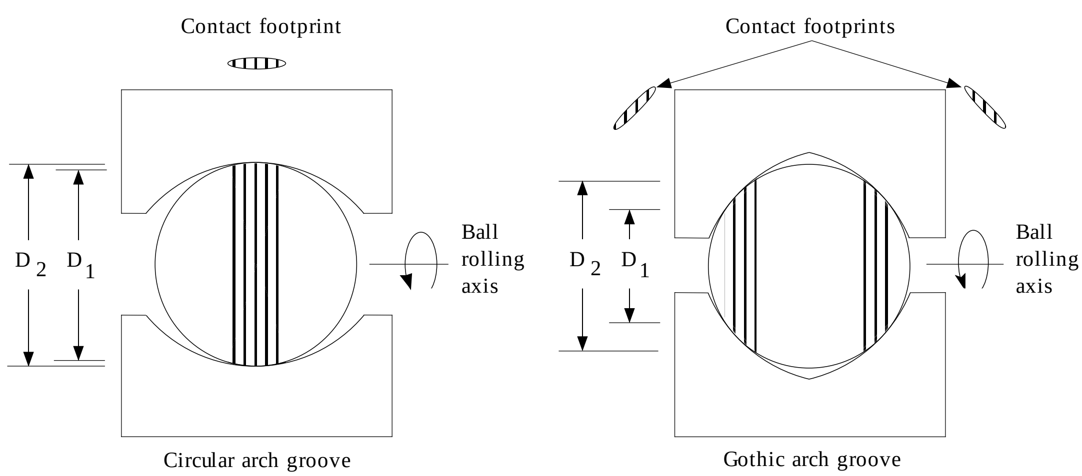
- **Compressive preloading uses an undersize spacer between two nuts.**
    - **This creates a face-to-face mounting situation:**
        - **Thermally stable if the nut is likely to be hotter than the leadscrew.**
    - **If the nut has an angular displacement imposed on it due to mounting errors:**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

- **Whenever 2 nuts are used, costs increase because of the need to manufacture 2 nuts which also have parallel faces.**

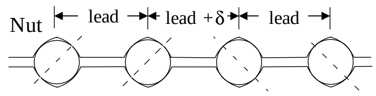


P-type preloading (use of oversize balls)

- **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 the ball is subjected to.**
    - **Because of skidding, this type of preload should not be used for precision systems.**
        - **In a heavily loaded milling machine, the balls are usually always primarily loaded in one direction or the other, so P-type preloading is effective and economical.**
    - **A circular arch groove typically has 3% slip during rolling compared to 40% for a Gothic arch groove:**



- **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 ransition point or "skip" by the preload amount.**