Precision Machine Design

Topic 20

Rotary motion power transmission elements[1]

Purpose:

This lecture discusses fundamental properties of Rotary motion power transmission elements.

Outline:

- **Error sources**
- **Gears**
- **Modular speed reducers**
- **Couplings**

"Push on - keep moving"

Thomas Morton

1 Special thanks to Layton Hale for reviewing this section, and providing invaluable suggestions and additions, particularly on the issue of anti-backlash gear design issues.

Error sources

- **Many factors contribute to the degradation of accuracy and controllability of a rotary power transmission system:**
    - **Form error in the device components causes:**
        - **Motion nonlinearity.**
        - **Speed variation.**
        - **Preload, and hence stiffness, variations.**
    - **Component misalignment causes:**
        - **Motion nonlinearity.**
    - **Backlash results from gaps between components and causes:**
        - **Temporary lack of motion upon torque reversal.**
    - **Friction causes:**
        - **Control problems.**
        - **Heat generation.**
        - **Wear.**

- **Transmission systems used to be used to increase the resolution of sensors.**
    - **Today it is best to mount a high accuracy sensor directly to the output shaft.**
- **Use good quality preloaded (zero backlash) components so the servosystem will not limit cycle.**
    - **Transmission accuracy is not as important with direct sensor measurement.**
    - **Backlash must be eliminated to ensure controllability (e.g., lead error is ok, but backlash is not).**

Gears[2]

- **Gears are often used for the following reasons:**
    - **To obtain a mechanical advantage to minimize motor current requirements.**
    - **To obtain the dynamic range required, for a reasonable cost.**
    - **To minimize the size of an actuator system.**
- **Different types of gears have been developed to:**
    - **Minimize noise.**
    - **Maximize power transmission efficiency.**
    - **Minimize torque ripple.**
    - **Increase load carrying capability.**
    - **Transfer power from oddly intersecting shafts.**
- **As the gear shape becomes more complex, it can become more difficult to manufacture and measure.**
    - **Backlash prevention strategies should accomodate gear inaccuracies.**

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[2] An excellent reference that discusses errors in gear trains, incuding statistical calculations for resultng errors in multistage systems, is George W. Michalec, Precision Gearing: Theory and Practice, John Wiley & Sons, New York, 1966.

Gear Errors

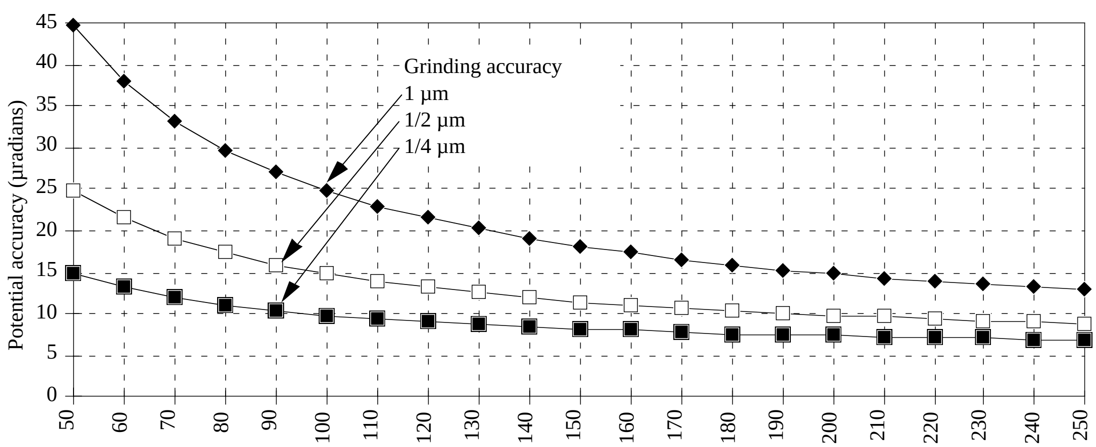
- **Variations in circular pitch or tooth thickness create the effect of a sinusoidal variation in the gear ratio.**
    - **Both also are a source of backlash.**
    - **Small gear ratio variations are not too difficult for a robust control system to compensate for.**
- **Backlash can cause limit cycling in the control system.**
- **Backlash is affected by (and required to accomodate):**
    - **Tooth thickness error**
    - **Tooth profile error**
    - **Deflection under load**
    - **Tooth wear**
    - **Center distance error**
    - **Pitch line radial error motion**
    - **Gear axis parallelism**
    - **Thermal expansion**
        - **The left four factors primarily affect the circumferential position of the contact point.**
        - **The right four factors primarily affect the effective center distance.**
        - **Some backlash is desired to allow for manufacturing errors, deflection under load, and thermal expansion.**

Tooth shape

- **Circumferential accuracy of gear dimensions is primarily affected by how the gear is manufactured.**
- **The angular error ε_{gear} in a gear is a function of:**
  - **The Abbe error in tooth location of the gear on the index table $r_{gear}\varepsilon_{index\ table}$.**
  - **The grinding process error δ_{grind}.**
  - **The gear radius r_{gear}:**

$$\varepsilon_{gear} = \frac{r_{gear}\,\varepsilon_{index\ table} + \delta_{grind}}{r_{gear}}$$

- **Precision indexing tables are commonly available that are accurate to one arc-second (4.8 μrad).**
- **Potential accuracy for gears ground on an index table with 1 arc-second accuracy:**



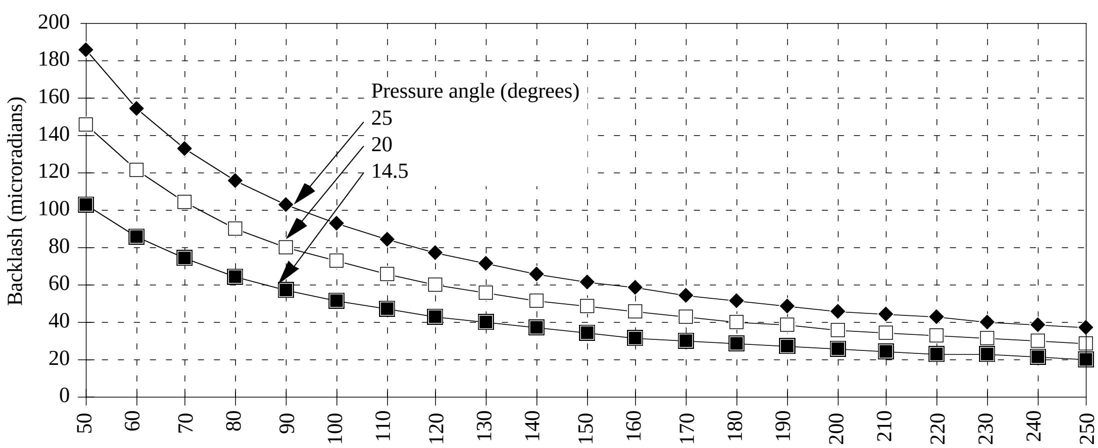
- **This error is for each gear in a gear set and is cumulative.**
- **Gears can be specially ground or lapped to achieve a few arc seconds of accuracy, but the cost can be very high.**

Center distance

- **An error in center distance location between gears will also affect their accuracy, predominantly by creating backlash.**
- **Consider two parallel lines which are at the pressure angle ϕ wrt a vertical line that connects two gears' centers.**
- **As the gear centers move apart by an error δ_{center}:**
  - **The distance δ_{tooth} the center distance moves in a direction tangent to its contact point increases.**
- **An approximation for the angular error $\varepsilon_{gear\ set}$ is:**

$$\varepsilon_{gear} = \frac{\delta_{center} \tan\phi}{r_{gear}}$$

- **For the greatest insensitivity to center distance errors, a small pressure angle is desired.**
- **Effect of a 10 micron center distance error on gear backlash:**

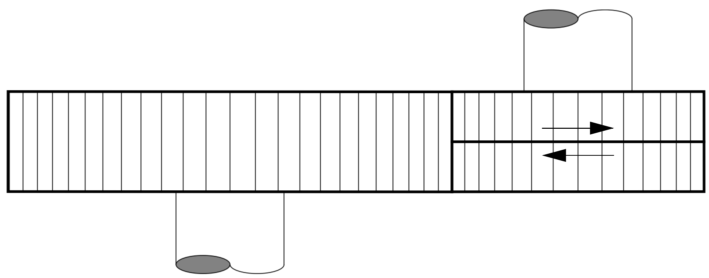


Pressure Angle

- **The transmission ratio between a single set of gears is just the ratio of the gears' pitch diameters (or numbers of teeth).**
- **The pressure angle is the angle of the contact force between the gear teeth relative to the tangent to the pitch circles.**
    - **The larger the pressure angle, the greater the tooth thickness, strength, and stiffness.**
    - **The larger the pressure angle, the greater the tooth forces:**
        - **Larger tooth forces create larger reaction forces on supporting shafts and bearings.**
- **For precision servocontrolled cutting applications, static stiffness is often of prime concern.**
    - **A large pressure angle is desired with a large shaft and support bearings to withstand the larger radial forces.**
- **For measuring applications where smoothness of motion is desired, fine teeth (a small pressure angle) are desired.**
- **A good compromise is a pressure angle of 20^{o} which has become a popular choice.**

Backlash reduction

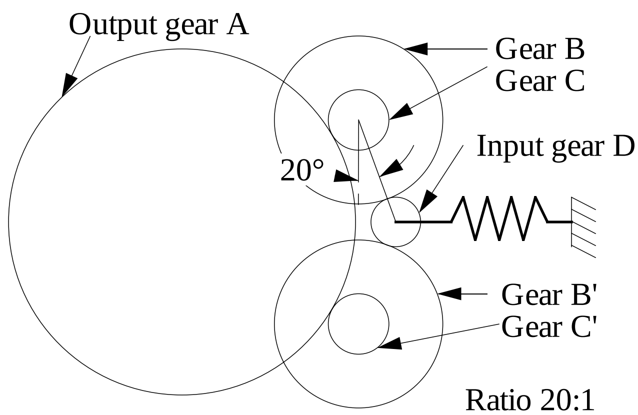
- To minimize backlash without the expense of grinding gears to very close tolerances:
  - Use a constant force or torque spring or hanging weight to keep the torque on the gears acting in one direction.
  - Use anti-backlash gears or dual pinion systems.
- Typically, anti-backlash gears are made by taking one gear in a pair and making it from at least two gears:



- The two gears are rotated relative to each other:
  - By using a set screw.
  - By a spring.
- One gear transmits torque in one direction and the other gear transmits torque in the other direction.
  - The preload ensures that tooth contact is maintained regardless of the direction of rotation.

- **Anti-backlash gears preloaded by a spring are easier to install.**
  - **Bi-directional torque capacity is limited by the spring preload force.**
- **Setscrew preloaded gears have high bidirectional torque capability.**
  - **Preload deflection is very low, so wear quickly eliminates preload.**
  - **It takes some skill to adjust anti-backlash gears whose preload is fixed by a setscrew.**

- **Alternatives: Dual pinion designs**[3]
  - **Two drive motors can be used with two gears to drive one large gear (single stage only).**
  - **Two pinions can be preloaded by a third driven gear that is wedged between them (possible with multistage units):**



  - **Input gear A and its motor are on a flexural bearing-spring system that keeps it driven between gears B and B'.**
  - **Gears C and C' are integral with gears B and B'.**
    - **The phase between the C and B and C' and B' gear teeth: must be exactly the same.**
  - **The C gears drive the output gear A.**
  - **If the motor gear is made to be disengagable:**
  - **A spindle can be driven at high speed by a separate motor.**
  - **For low speed servo controlled motion, the anti-backlash gear system and servo motor can be engaged.**

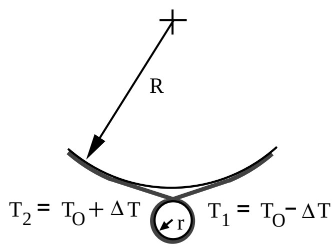
[3] For details, see Hale, L.C., Slocum, A.H., "Design of Anti-Backlash Transmissions for Precision Position Control Systems", Precision Engineering, Vol. 16, No. 4, Oct. 1994, pp 244-258. For further information, contact Layton Hale, LLNL, PO Box 808, L-792, Livermore, CA 94550

Worm gears

- **The same type of accuracy and backlash considerations apply to worm gears as to spur gears.**
- **With worm gears the contact between them is sliding so friction and wear levels are higher than for spur gears.**
  - **Depends on hydrodynamic lubrication for efficiency.**
  - **Small lead angle worms are susceptible to stick-slip when decelerating very large loads.**
- **The simplicity of a worm gear system makes it ideal for precision machines where:**
  - **High transmission ratios are desired.**
  - **Servocontrolled angular position rates are generally slow.**
- **Preloaded worm gears are sometimes used to control the position of:**
  - **Rotary index tables**
  - **Rotary servocontrolled axes on machining centers.**

Modular speed reducers

- **There are many types of high quality modular speed reducers available:**
  - **Planetary gear drives (backlash)**
  - **Harmonic gear drives (preloaded)**
  - **Cycloidal drives (preloaded)**
  - **Traction roller drives (preloaded)**
  - **Wire capstan drives**[4] **(preloaded)**



- **Care should be used when purchasing a drive system for a position control application.**
  - **Often the servomotor, resolver, and controller are meant for speed control only.**
  - **Test a unit before a particular unit is specified unless it has a history of success in similar applications.**

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[4] Marketed as a *Roto-Lok* drive from Sagebrush Technology Inc., 10300-A Constitution NE, Albuquerque, NM 87112; (505) 299-6623.

Couplings

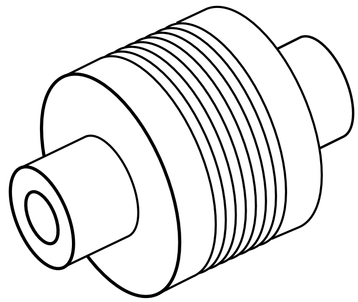
- **Without a coupling between shafts, bearings would be overloaded and systems would soon fail.**
- **Couplings are attached with setscrews and keys, or circumferential clamps.**
  - **The former can have "backlash" and cause eccentricity errors.**
  - **The latter can slip under high torque.**
  - **Use a combination of both, and pot the key in epoxy to prevent "backlash" under high reversing loads.**
- **In order to avoid periodic errors, a constant velocity flexible coupling should be used.**
  - **Manufacturing tolerances limit bore alignment in flexible couplings.**
- **An estimate of flexible coupling accuracy can be obtained by assuming that it is the product of two errors.**
  - **The first error is the error obtained if a pin-in-slot coupling was used between the two shafts.**
  - **The second error is the error of the flexible coupling due to bore misalignment:**

$$\varepsilon_{\text{flexible coupling}} = \left[\frac{\text{shaft eccentricity}}{\text{small shaft radius}}\right]\left[\frac{\text{coupling bore eccentricity}}{\text{small bore radius}}\right]$$

  - **Remember, this is only a back-of-the-envelop estimate!**
- **Consider coupling a 10 mm diameter shaft to a 30 mm diameter shaft where the shaft eccentricity is 0.05 mm.**
  - **The coupling's bores are assumed to have a 0.025 mm eccentricity due to manufacturing error.**
  - **The total maximum coupling error for the system can be estimated to be 17 microradians.**

- **There are five basic types of couplings for precision applications that can handle bidirectional torques:**
  - **Metal bellows**
  - **Beam**
  - **Link**
  - **Diaphragm (flexible disk)**
  - **Center of percussion**
  - **Belt**
- **Whichever type of coupling is chosen, a set screw should never be used to clamp a coupling to a precision shaft.**
- **A split ring that squeezes the shaft upon tightening of a bolt should always be used.**

Metal bellows couplings

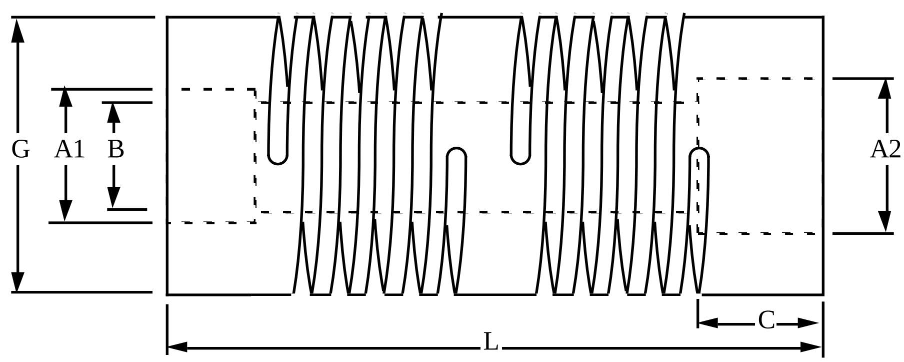


- Inexpensive because they made in standard sizes and they do not need to be able to hold pressure or vacuum.
- Provide large misalignment capability, with the least decrease in torsional stiffness.
- They are generally used in applications where torque levels are less than about 10 N-m (90 in-lbf).
- For most precision machine applications, speed is not usually a limiting factor in metal bellows coupling's design.

Beam couplings

- **Made by cutting slots in a cylindrical shaft thereby creating a series of flexural bearings.**

- **Helical™ coupling is formed by cutting a helical groove in a hollow shaft so the web thickness decreases with the radius** (Courtesy of Helical Products Company, Inc.):



- **They are simple to design with and provide very repeatable performance.**

Center of percussion couplings[5]

- **Most couplings will transmit radial forces from one shaft to another.**
- **It is important to prevent vibrational forces from the motor shaft from being transmitted to the spindle.**
- **If you take a pencil laid flat on the table and hit one end:**
  - **The pencil rotates about a point which is known as the *center of percussion*.**
- **Baseball players know that unless the ball hits the bat at the right (sweet) spot, the impact will sting their hands.**
- **If the pencil is now a drive shaft with one end being attached to the output shaft of the motor:**
  - **The driveshaft should be attached to the spindle at the center of percussion point.**
- **It is impractical to have a long shaft protruding beyond the coupling point:**
  - **Use a shaft with a heavy weight near the coupling point.**

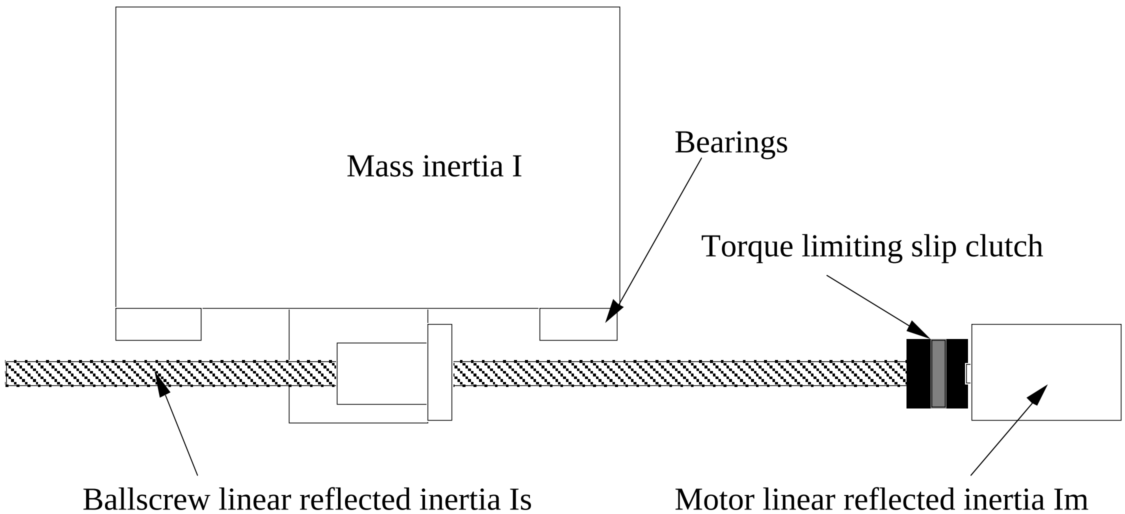
[5] Available from Professional Instruments Inc., 7800 Powell Road, Hopkins, MN 55343

Belt couplings

- **If a long springy continuous fiber belt is used to transmit power between shafts:**
    - **Small radial motions will insignificantly affect the belt tension.**
    - **The belt also serves to help thermally isolate the motor from the spindle.**
- **As spindle accuracy requirements head towards the microinch and better realm:**
    - **Even the magnetic asymmetries in electric motors can cause unacceptable levels of asynchronus spindle motion.**
- **A single felt belt can act as a coupling, but it usually has a low power transmission capability.**
- **Multiple belts are never perfectly matched.**
    - **They invariably oscillate radially between pulleys and can cause significant radial error motions.**

Slip clutches

- **A slip clutch is sometimes used to prevent the ballscrew from pushing too hard on an axis:**
  - **In the event of a crash.**
  - **To prevent overloading an axis.**



- **Compliant energy dissipating buffers should always be installed at the end of travel.**

- **When an axis crashes into a "rigid" body, inertial forces dominate.**
- **Optimal transmission ratio requirements lead to the inertia of the ballscrew and motor equaling the inertia of the axis.**
- **If sliding contact bearings have been used:**
  - **The motor inertia may be substantial, owing to larger static force generating requirements.**
    - **In this case, a slip clutch may be desireable.**
- **When low friction bearings are used:**
  - **The motor inertia is usually small compared to the ballscrew inertia, and thus a slip clutch is not needed.**
  - **A current limiter on the motor will prevent motor burnout.**
  - **The added force from the ballscrew being driven by the motor is insignificsant compared to the crash forces.**