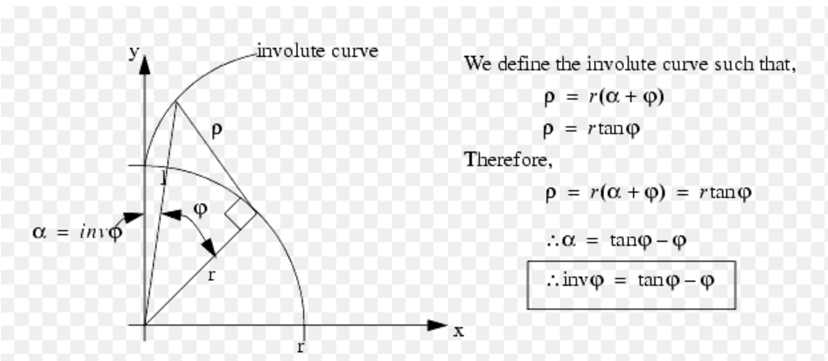
Precision Machine Design-Power transmission elements

1. Rotary power transmission

Rotary power sources, e.g. motors are most common, and rotary power transmission is one of key issues for power transmission. As motor output is usually of high speed, thus speed reduction with torque amplification case is generally required for precision applications.

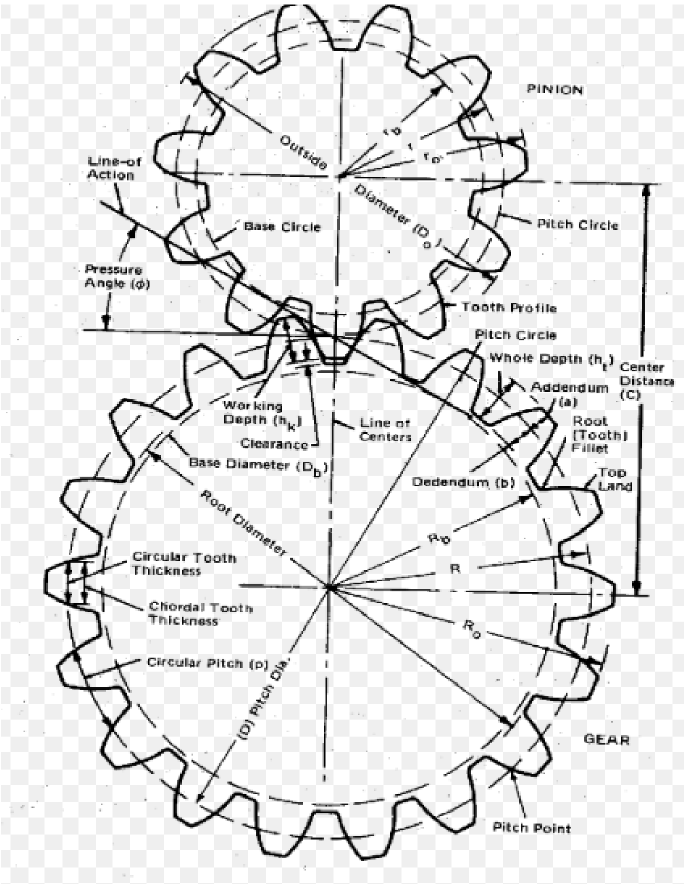
1) Gears

Gear is one of the frequently used elements for rotary transmission, and it is one of the rolling based elements, thus giving very small friction coefficient, and the involute gear is using the involute curve formed by the intersection of tangent line from the base circle and the line of involute angle, defined as inv φ= tan φ – φ, where gear nomenclature is shown in the fig.



(source: Engineer on a disk)

The transmission ratio, for the spur gear, is given by the ratio of D1:D2, the pitch diametres engaged, and is usually used in Transmission ratio up to 10.



General nomenclature for spur gear

(source:katheenhalme.com)

Tooth thickness error (or error in circular pitch), tooth profile error, gear deflection under load, tooth wear, error in the centre distance, radial error motion in pitch line, gear axis parallelism, thermal expansion are typical error sources in gear transmission, resulting in non-precise transmission ratio, and backlash can be occurring in the rotation reversing.

Pressure angle is defined as the angle between the line of pressure and the line of centre connection, and they are typically 14.5, 20, 25 deg. Larger pressure angle indicates larger thickness of gear tooth, giving stronger and stiffer gear tooth.

For the centre distance error, δ_{centre}, the resulting angular error, or backlash, ε_{gear}, in the gear is approximately

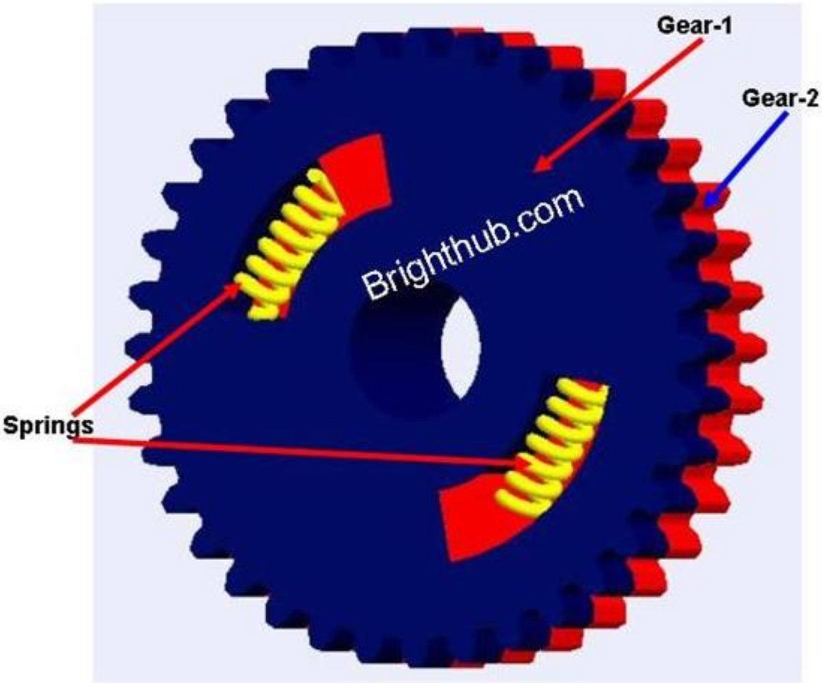
$\varepsilon_{gear}=\delta_{centre} \tan\alpha / R_{gear}$

where α=Pressure angle, R_{gear}= Radius of larger gear

Ex) δ_{centre}=20um, R_{gear}=20mm, Pressure angle α=25deg;

Backlash, ε_{gear}=20(0.466)/0.02=466 [urad] ≒97[arcsec];

The anti-backlash gears can be used to minimize the backlash induced, in which two gears rotating relatively, thus one gear transmit torque in forward direction and other gear transmits torque in reverse direction, preloading with each other.



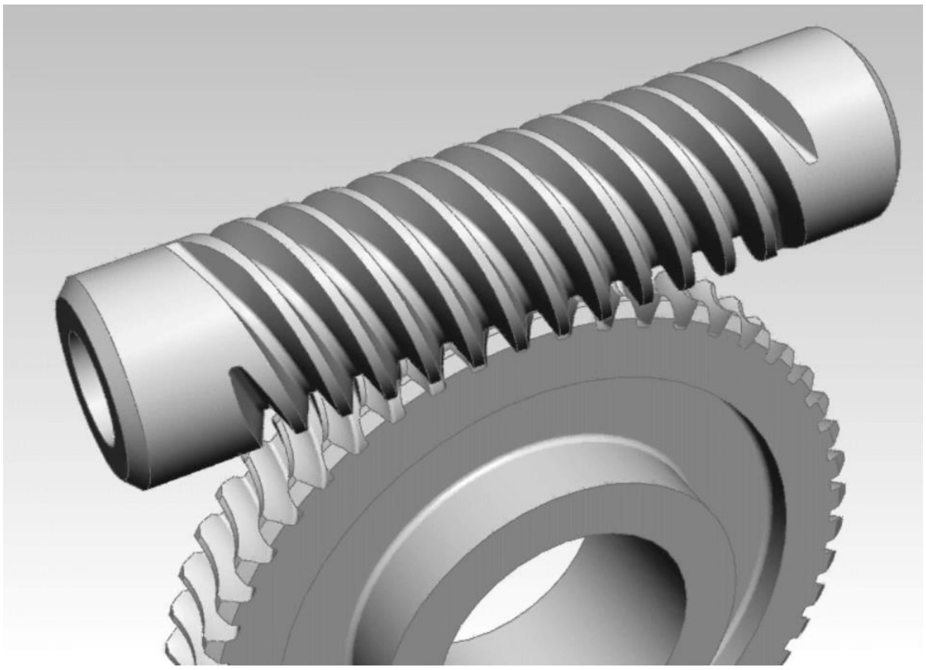
Anti-backlash gear (source: Brighthub.com)

Worm gear

Worm gears have more complicated tooth geometry than spur gears, but they can give very high transmission ratio such as

Transmission ratio= R/p_{worm}

where R=radius of driven gear, p_{worm}=pitch of the work gear. Worm gears are frequently used in precision rotary indexing table and rotary axis in machine tools.



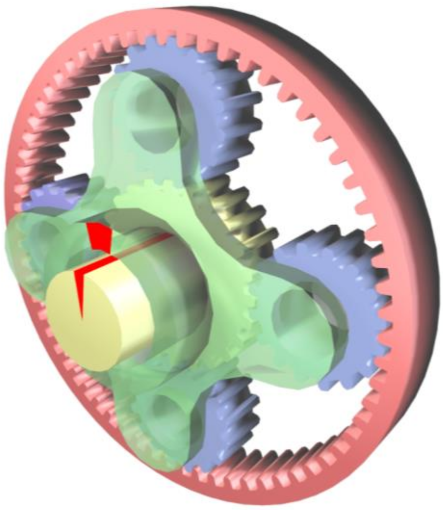
Worm gear (Source:Wikipedia)

Planetary (epicyclic) speed reducer (유성기어감속기)

:Consists of Ring gear(Outer gear), Sun gear(Centre gear), and planet pinions(Planetary pinions), in order to give higher load and torque capability, by sharing the loads woth multi-planet pinons.

The ring gear is rotating in one direction, the planetary pinions are rotating, then the centre gear is rotating in opposite direction. The transmission ratio is then

Transmission ratio=$R_{sun}/(R_{ring}-R_{sun})$



Epicyclic speed reducer (source:Wikipedia)

Harmonic speed reducer (하모닉 감속기어)

:Large ring gear with internal tooth(blue), flexible spline with external tooth(red), two cam rollers(green)

Harmonic speed reducer (source:modified from Wikipedia)

Very similar principle to the planetary speed reducer; where the flexible spline and two cam rollers are replacing the planet pinions. The transmission ratio, TR, is

$TR=N_{spline}/(N_{ring}-N_{spline})$

Where N_{spline} and N_{ring} are the number of teeth for the spline and ring, respectively.

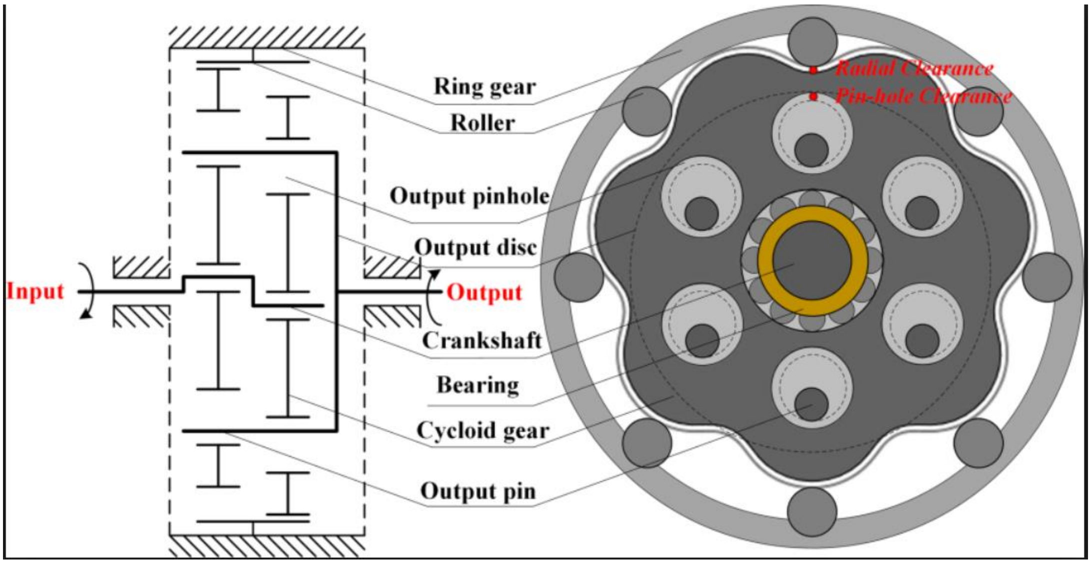
Ex) When $N_{ring}=202$, $N_{spline}=200$;

then transmission ratio, TR=200/(202-200)=100, giving 100:1 , giving very high transmission ratio.

Cycloidal speed reducer (or epitrochoidal drive)

:Ring, input shaft linked with trochoidal cam, trochoidal shaped cam of N_{iuput}-1 lobes, N_{input} rollers rolling between the trochoidal cam and ring, N_{output} rollers on output holes in the trochoidal cam, output shaft linked to the output rollers.

As input shaft is rotating, the trochoidal cam of N_{input}-1 lobes is rotating with N_{input} rollers rolling on the ring. The output shaft is rotating with the N_{output} rollers on the output holes. Thus this drive provides very high transmission ratio with very high stiffness and load capacity.



(source: Xuan Li, etal. Analysis of cycloidal speed reducer considering profile modification and clearance fit ouput mechanism, J. of Mechanical Design)

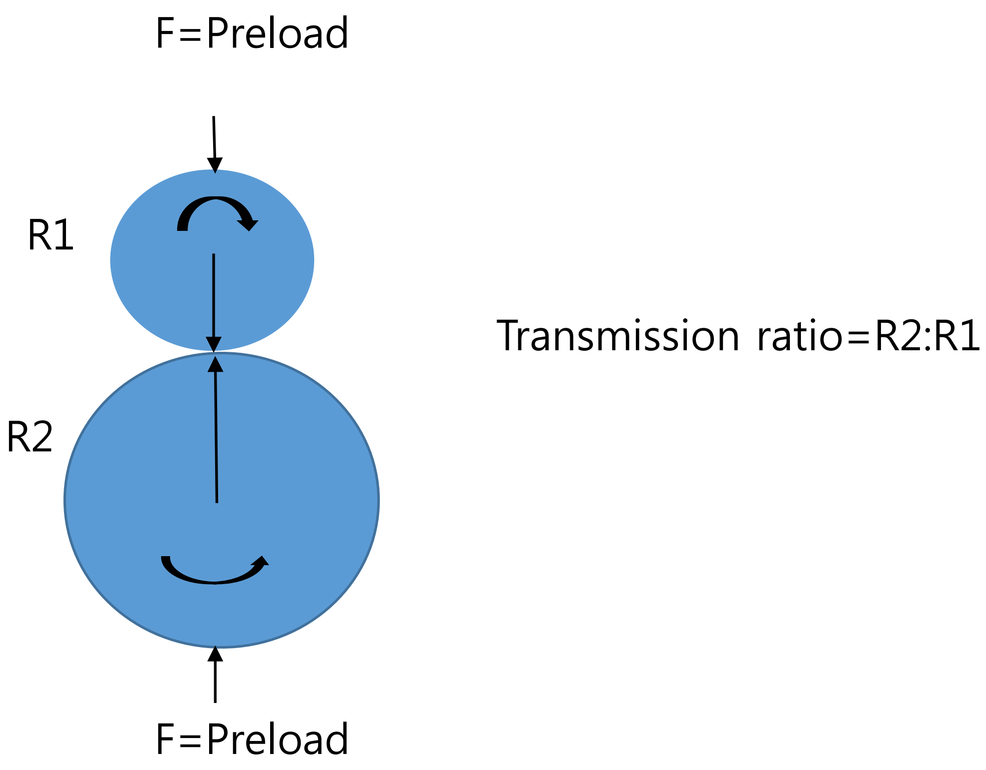
Transmission ratio, TR, is

$TR=(N_{input}-1)N_{output}/[N_{input}-N_{output}]$

Thus, when $N_{input}=8$, $N_{output}=6$; then $TR=(8-1)6/(8-6)=21:1$

2) Traction Drives

When the load is low, and similar transmission mission ratio as the gear transmission is required, the traction drive can be a good alternative solution, because there are some drawbacks of gears such as manufacturing difficulty (cost), and potential vibration and noise caused by non-precise manufacturing/adjusting. The traction rollers are replacing the gears, and preloading against each other.



Tangential stiffness, K_{tan} is

$K_{tan}=\partial F_{tan}/\partial \delta_{tan}=1/(\partial \delta_{tan}/\partial F_{tan})$

$= 4aE(1-F_{tan}/\mu F)^{1/3}/[(2-\nu)(1+\nu)]$ with slip

(If $F_{tan}=0$, there is no slip between the interface)

where a is the contact radius of equivalent system, and

$a=[3FR_e/2E_e]^{1/3}$ and

$E=E_e$=equivalent modulus of elasticity

$=1/[(1-\nu_1^2)/E_1+(1-\nu_2^2)/E_2]$

Re=equivalent radius

$=1/[1/R_{1major}+1/R_{1minor}+1/R_{2major}+1/R_{2minor}]$

μ=friction coefficient, typically 0.1 for this case.

Thus the torque transmitted, T, in this case,

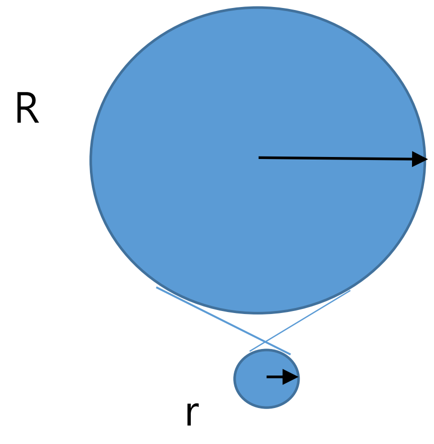
T=μFR2 [Nm]

Traction drive has the potential to achieve near perfect accuracy with no backlash, under properly adjusted conditions. Sometimes tractive fluid can be used for effective coefficient of friction to be about 0.1, and to reduce wear and slip damage at the contact interface.

3) Wire capstan drives

For small range of motion, the wire capstan drive can be used instead of gear transmission, without large radial bearing loads due to preload.

The transmission ratio=R:r= upto 50:1 achievable.



4) Belt and chains

Belts and chains are commonly used in precision machines due to simple adjustment with quite accurate transmission.

Tension adjustment is essential, via by allowing one shaft movable, or by using an idle pulley with adjustable position.

V-belts

V belts are one of the most cost-effective ways to transmit power between parallel shafts. V belts wedge into the pulley, thus the power is efficiently transmitted with the increased pressure between the belts and pulley. Preload is required to seat the belt into the pulley, adding radial load to the shaft. The V belts make large area contact between the belt and pulley, making relative slip, generating heat.

The V belts are mainly used in power transmission from motor to main spindle in machine tools.

Timing belts

Timing belt has teeth to transmit power into the toothed pulley. It bends over a pitch diameter with minimum cogging. The backlash can be prevented by preload It when the direction of motion is reversed. The preloaded timing belts has better performance due to full engagement of teeth by the averaging effect. This is frequently used for precision power transmission between the servo motor and shaft, unless direct drive motor is used.

Flat belts

Flat belts can have high efficiency in high speed application due to less heat generation and reverse bendable use, and Kevlar and spring steel are major materials for the belts, while the V belts and chains are commonly used for low speed high torque application.

Roller chain

Roller chain can transmit significantly higher loads than the belt transmission, and is one of least expensive cost. As the roller chain is rotating over the sprocket having small number of teeth, it may have some significant sinusoidal load variation during transmission, and the averaging effect is quite small, thus it is not desirable for transmission of precision motion. Roller chain can be used for non-precise, low speed application such as motion of chambers in long furnace tunnel, counter weight movement, etc.

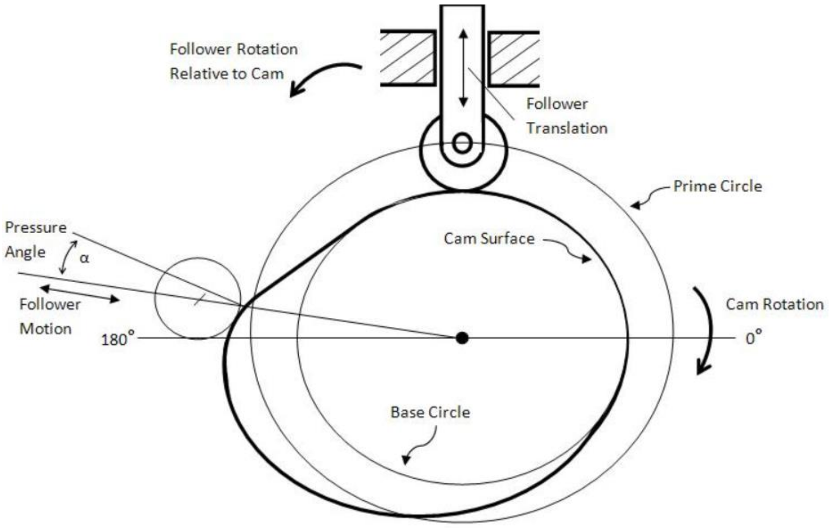
Roller chain over the sprocket (source:Wikipedia)

5) Cams and couplings

Cam

Cam is to transmit the rotary motion into irregular linear motion that follows the profile of cam surface as it rotates.

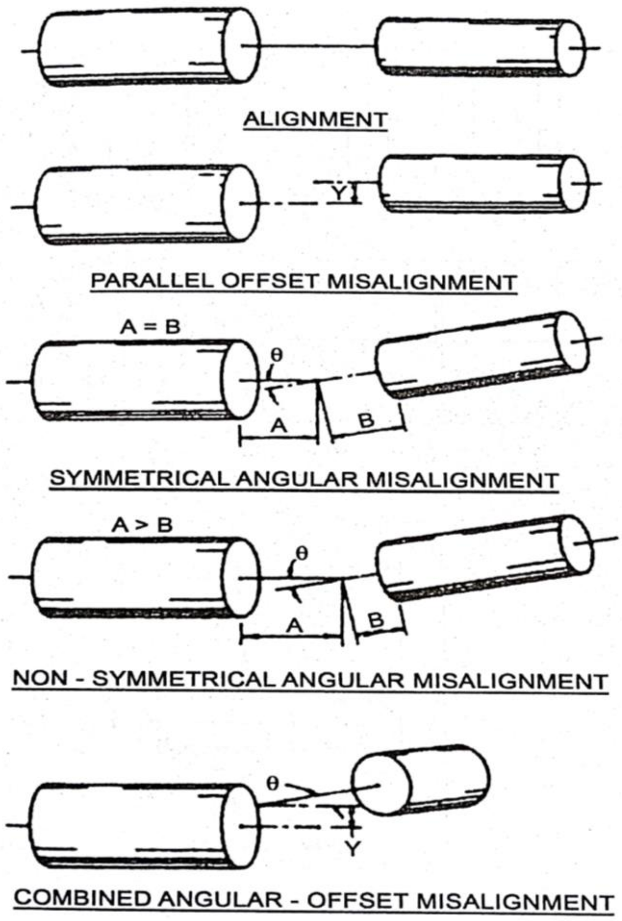
Cam provides a very robust mechanical motion with very simple design and low cost, thus it is widely used such as in automobile, screw machines, and nonround parts machining. The software cam also can be used by NC or software programming in machine tools.



Cam Mechanism (source:Wikipedia)

Couplings

Misalignment in shaft connection causes not only periodic errors for transmitted motion, but may cause catastrophe leading to machine broken or critical damage due to fatigue failure, etc. Coupling are thus vital mechanical elements that must be considered during any kind of shaft connection. Several modes of misalignment of shafts are shown in the figure.



Misalignment modes (Source: Eugene I. Rivin, 'Handbook on Stiffness and Damping in Mechanical Design' ASME Press,2010)

When the couplings are chosen, the permissible misalignment modes and amount must be considered, together with the life time in millions of cycles, typically. For many precision application, the misalignment errors are typically 20um in offset and 200urad in angle; but may exceed 10 times of these unless special care is taken.

<u>Oldham coupling</u> is traditional metal coupling, in which radial

misalignment is accommodated by sliding contact along the slots between the two shaft surfaces. Thus it gives very high torsional stiffness, but very little radial stiffness. It is widely used in practical machine design.

Oldham coupling (source:Wikipedia)

Metal bellows coupling consists of metal bellows, allowing flexible coupling in all direction but relatively small torsional stiffness of typically less than 10Nm, and with limited life time in cyclic motion.

Metal bellows coupling (source:Wikipedia)

Helical beam coupling is a kind of hollow cylinder, in which helix or spiral patterns are shaped. Thus it can withstand reasonable bending and torsional load to accommodate the radial and angular misalignment. The axial motion also can be allowed by the coil movement. No backlash and constant velocity coupling are also expected. Most widely used in rotating machinery such as in ball screws, encoders, gear boxes, pumps, conveyor system, and rollers, etc.

High strength aluminum for encoder coupling, high strength SUS for high torque capacity with corrosion resistance.

Helical flexible coupling (source:Wikipedia)

Diaphragm coupling, or Flexible disc coupling typically is of about one-third less radial stiffness, but about twice higher torsional stiffness than other flexible couplings. Thus it is also widely used in high torque application. Angular misalignment is primary target and radial misalignment is also permissible with extra discs.

Flexible disc coupling (source: Rembrandt, inc)