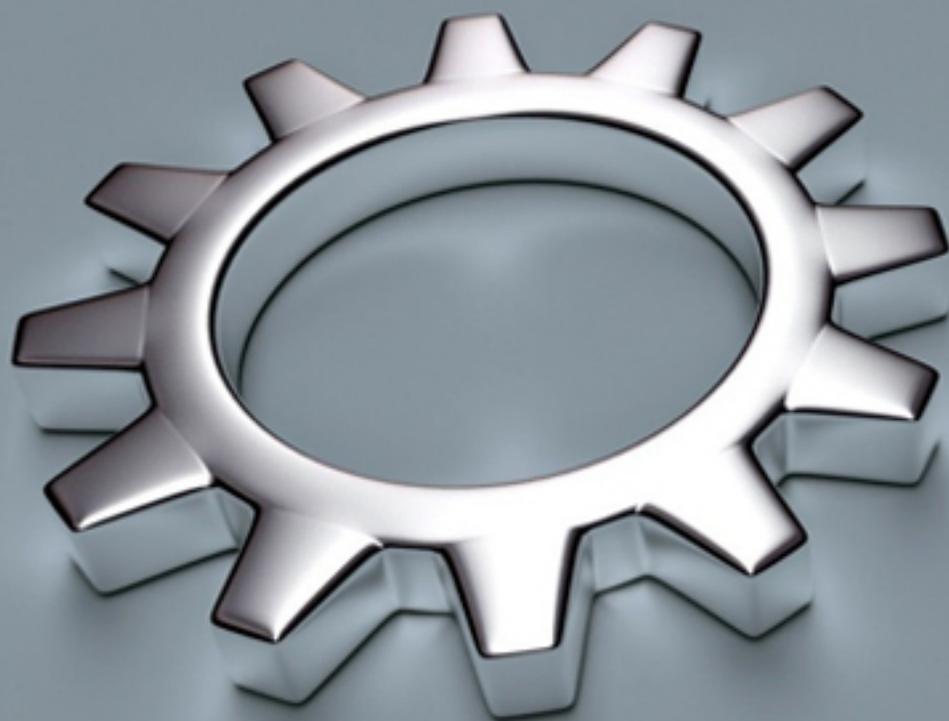


Handbook of
Gear
Engineering, Mechanics and Systems



Nadene Schuster
Refugio Negrón

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Table of Contents

Chapter 1 - Gear

Chapter 2 - Bevel Gear

Chapter 3 - Spiral Bevel Gear and Herringbone Gear

Chapter 4 - Worm Drive

Chapter 5 - Epicyclic Gearing

Chapter 6 - Harmonic Drive and Non-Circular Gear

Chapter 7 - Backlash (Engineering)

Chapter 8 - Bicycle Gearing

Chapter 9 - Continuously Variable Transmission

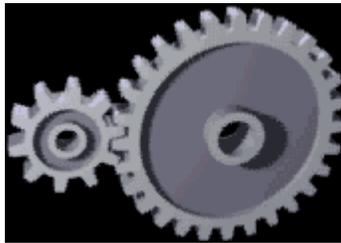
Chapter 10 - Differential (Mechanical Device)

Chapter 11 - Transmission (Mechanics)

Chapter 12 - Gear Ratio

Chapter 1

Gear



Two meshing gears transmitting rotational motion. Note that the smaller gear is rotating faster. Although the larger gear is rotating less quickly, its torque is proportionally greater.

A **gear** or more correctly a "gear wheel" is a rotating machine part having cut *teeth*, or *cogs*, which *mesh* with another toothed part in order to transmit torque. Two or more gears working in tandem are called a *transmission* and can produce a mechanical advantage through a gear ratio and thus may be considered a simple machine. Geared devices can change the speed, magnitude, and direction of a power source. The most common situation is for a gear to mesh with another gear, however a gear can also mesh a non-rotating toothed part, called a rack, thereby producing translation instead of rotation.

The gears in a transmission are analogous to the wheels in a pulley. An advantage of gears is that the teeth of a gear prevent slipping.

When two gears of unequal number of teeth are combined a mechanical advantage is produced, with both the rotational speeds and the torques of the two gears differing in a simple relationship.

In transmissions which offer multiple gear ratios, such as bicycles and cars, the term **gear**, as in *first gear*, refers to a gear ratio rather than an actual physical gear. The term is used to describe similar devices even when gear ratio is continuous rather than discrete, or when the device does not actually contain any gears, as in a continuously variable transmission.

The earliest known reference to gears was circa A.D. 50 by Hero of Alexandria, but they can be traced back to the Greek mechanics of the Alexandrian school in the 3rd century B.C. and were greatly developed by the Greek polymath Archimedes (287–212 B.C.). The Antikythera mechanism is an example of a very early and intricate geared device, designed to calculate astronomical positions. Its time of construction is now estimated between 150 and 100 BC.

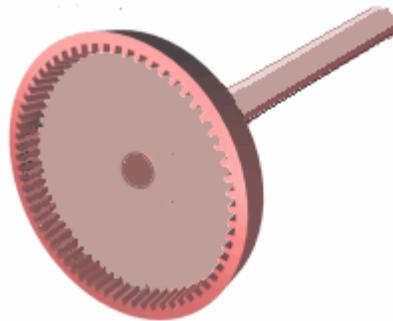
Comparison with other drive mechanisms

The definite velocity ratio which results from having teeth gives gears an advantage over other drives (such as traction drives and V-belts) in precision machines such as watches that depend upon an exact velocity ratio. In cases where driver and follower are in close proximity gears also have an advantage over other drives in the reduced number of parts required; the downside is that gears are more expensive to manufacture and their lubrication requirements may impose a higher operating cost.

The automobile transmission allows selection between gears to give various mechanical advantages.

Types

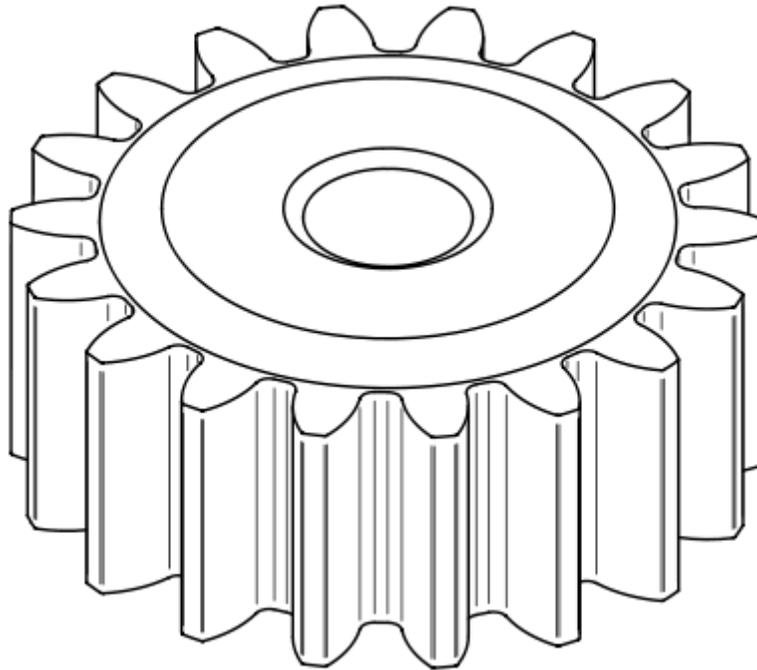
External vs. internal gears



Internal gear

An *external gear* is one with the teeth formed on the outer surface of a cylinder or cone. Conversely, an *internal gear* is one with the teeth formed on the inner surface of a cylinder or cone. For bevel gears, an internal gear is one with the pitch angle exceeding 90 degrees. Internal gears do not cause direction reversal.

Spur



Spur gear

Spur gears or *straight-cut gears* are the simplest type of gear. They consist of a cylinder or disk with the teeth projecting radially, and although they are not straight-sided in form, the edge of each tooth is straight and aligned parallel to the axis of rotation. These gears can be meshed together correctly only if they are fitted to parallel shafts.

Helical



Helical gears
Top: parallel configuration
Bottom: crossed configuration

Helical gears offer a refinement over spur gears. The leading edges of the teeth are not parallel to the axis of rotation, but are set at an angle. Since the gear is curved, this angling causes the tooth shape to be a segment of a helix. Helical gears can be meshed in a *parallel* or *crossed* orientations. The former refers to when the shafts are parallel to each other; this is the most common orientation. In the latter, the shafts are non-parallel, and in this configuration are sometimes known as "skew gears".

The angled teeth engage more gradually than do spur gear teeth causing them to run more smoothly and quietly. With parallel helical gears, each pair of teeth first make contact at a single point at one side of the gear wheel; a moving curve of contact then grows gradually across the tooth face to a maximum then recedes until the teeth break contact at a single point on the opposite side. In spur gears teeth suddenly meet at a line contact

across their entire width causing stress and noise. Spur gears make a characteristic whine at high speeds and can not take as much torque as helical gears. Whereas spur gears are used for low speed applications and those situations where noise control is not a problem, the use of helical gears is indicated when the application involves high speeds, large power transmission, or where noise abatement is important. The speed is considered to be high when the pitch line velocity exceeds 25 m/s.

A disadvantage of helical gears is a resultant thrust along the axis of the gear, which needs to be accommodated by appropriate thrust bearings, and a greater degree of sliding friction between the meshing teeth, often addressed with additives in the lubricant.

For a crossed configuration the gears must have the same pressure angle and normal pitch, however the helix angle and handedness can be different. The relationship between the two shafts is actually defined by the helix angle(s) of the two shafts and the handedness, as defined:

$$E = \beta_1 + \beta_2 \text{ for gears of the same handedness}$$

$$E = \beta_1 - \beta_2 \text{ for gears of opposite handedness}$$

Where β is the helix angle for the gear. The crossed configuration is less mechanically sound because there is only a point contact between the gears, whereas in the parallel configuration there is a line contact.

Quite commonly helical gears are used with the helix angle of one having the negative of the helix angle of the other; such a pair might also be referred to as having a right-handed helix and a left-handed helix of equal angles. The two equal but opposite angles add to zero: the angle between shafts is zero – that is, the shafts are *parallel*. Where the sum or the difference (as described in the equations above) is not zero the shafts are *crossed*. For shafts *crossed* at right angles the helix angles are of the same hand because they must add to 90 degrees.

Double helical



Double helical gears

Double helical gears, or *herringbone gear*, overcome the problem of axial thrust presented by "single" helical gears by having two sets of teeth that are set in a V shape. Each gear in a double helical gear can be thought of as two standard mirror image helical gears stacked. This cancels out the thrust since each half of the gear thrusts in the opposite direction. Double helical gears are more difficult to manufacture due to their more complicated shape.

For each possible direction of rotation, there are two possible arrangements of two oppositely-oriented helical gears or gear faces. In one possible orientation, the helical gear faces are oriented so that the axial force generated by each is in the axial direction away from the center of the gear; this arrangement is unstable. In the second possible orientation, which is stable, the helical gear faces are oriented so that each axial force is toward the mid-line of the gear. In both arrangements, when the gears are aligned correctly, the total (or *net*) axial force on each gear is zero. If the gears become misaligned in the axial direction, the unstable arrangement generates a net force for disassembly of the gear train, while the stable arrangement generates a net corrective force. If the direction of rotation is reversed, the direction of the axial thrusts is reversed, a stable configuration becomes unstable, and *vice versa*.

Stable double helical gears can be directly interchanged with spur gears without any need for different bearings.

Bevel

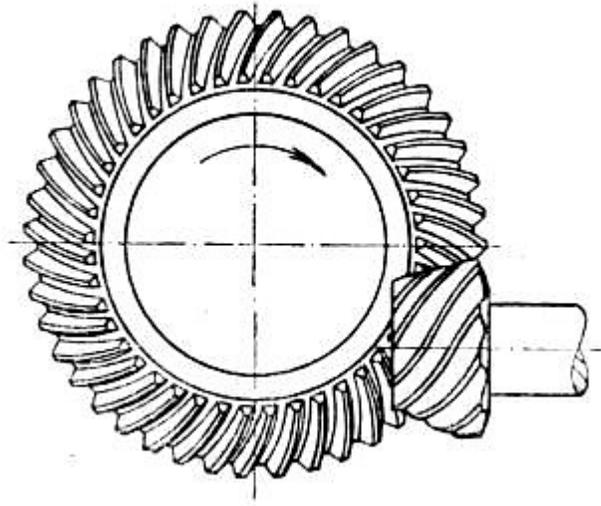


Bevel gear

A bevel gear is shaped like a right circular cone with most of its tip cut off. When two bevel gears mesh their imaginary vertices must occupy the same point. Their shaft axes also intersect at this point, forming an arbitrary non-straight angle between the shafts. The angle between the shafts can be anything except zero or 180 degrees. Bevel gears with equal numbers of teeth and shaft axes at 90 degrees are called *miter gears*.

The teeth of a bevel gear may be straight-cut as with spur gears, or they may be cut in a variety of other shapes. *Spiral bevel gear* teeth are curved along the tooth's length and set at an angle, analogously to the way helical gear teeth are set at an angle compared to spur gear teeth. *Zerol bevel gears* have teeth which are curved along their length, but not angled. Spiral bevel gears have the same advantages and disadvantages relative to their straight-cut cousins as helical gears do to spur gears. Straight bevel gears are generally used only at speeds below 5 m/s (1000 ft/min), or, for small gears, 1000 r.p.m.

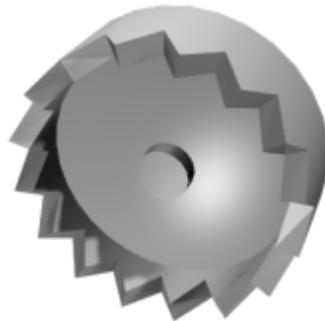
Hypoid



Hypoid gear

Hypoid gears resemble spiral bevel gears except the shaft axes do not intersect. The pitch surfaces appear conical but, to compensate for the offset shaft, are in fact hyperboloids of revolution. Hypoid gears are almost always designed to operate with shafts at 90 degrees. Depending on which side the shaft is offset to, relative to the angling of the teeth, contact between hypoid gear teeth may be even smoother and more gradual than with spiral bevel gear teeth. Also, the pinion can be designed with fewer teeth than a spiral bevel pinion, with the result that gear ratios of 60:1 and higher are feasible using a single set of hypoid gears. This style of gear is most commonly found driving mechanical differentials; which are normally straight cut bevel gears; in motor vehicle axles.

Crown



Crown gear

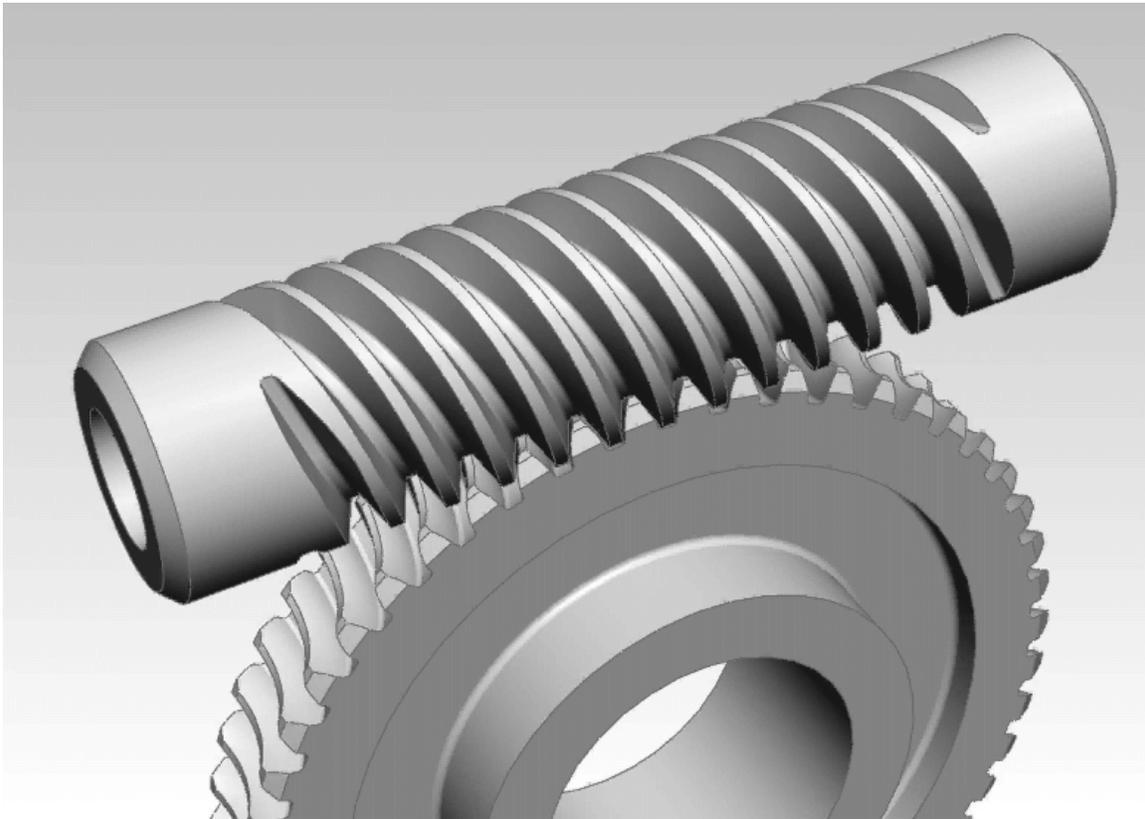
Crown gears or *contrate gears* are a particular form of bevel gear whose teeth project at right angles to the plane of the wheel; in their orientation the teeth resemble the points on a crown. A crown gear can only mesh accurately with another bevel gear, although crown

gears are sometimes seen meshing with spur gears. A crown gear is also sometimes meshed with an escapement such as found in mechanical clocks.

Worm



Worm gear



4-start worm and wheel

Worm gears resemble screws. A worm gear is usually meshed with an ordinary looking, disk-shaped gear, which is called the *gear*, *wheel*, or *worm wheel*.

Worm-and-gear sets are a simple and compact way to achieve a high torque, low speed gear ratio. For example, helical gears are normally limited to gear ratios of less than 10:1 while worm-and-gear sets vary from 10:1 to 500:1. A disadvantage is the potential for considerable sliding action, leading to low efficiency.

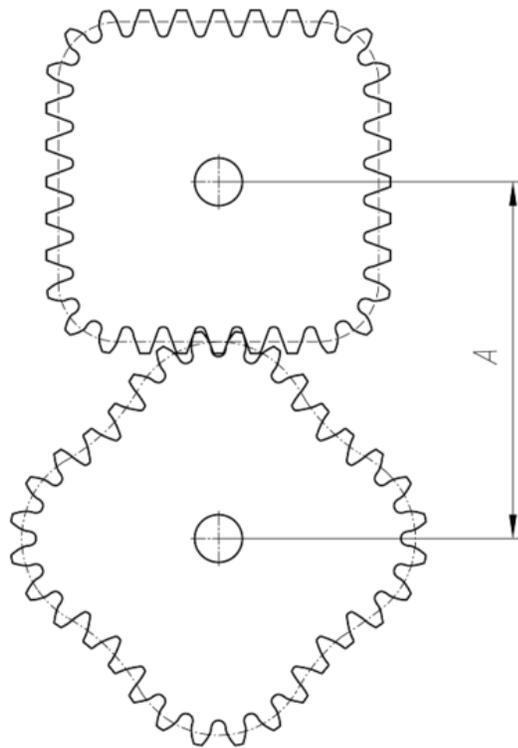
Worm gears can be considered a species of helical gear, but its helix angle is usually somewhat large (close to 90 degrees) and its body is usually fairly long in the axial direction; and it is these attributes which give it its screw like qualities. The distinction between a worm and a helical gear is made when at least one tooth persists for a full rotation around the helix. If this occurs, it is a 'worm'; if not, it is a 'helical gear'. A worm may have as few as one tooth. If that tooth persists for several turns around the helix, the worm will appear, superficially, to have more than one tooth, but what one in fact sees is the same tooth reappearing at intervals along the length of the worm. The usual screw nomenclature applies: a one-toothed worm is called *single thread* or *single start*; a worm with more than one tooth is called *multiple thread* or *multiple start*. The helix angle of a worm is not usually specified. Instead, the lead angle, which is equal to 90 degrees minus the helix angle, is given.

In a worm-and-gear set, the worm can always drive the gear. However, if the gear attempts to drive the worm, it may or may not succeed. Particularly if the lead angle is small, the gear's teeth may simply lock against the worm's teeth, because the force component circumferential to the worm is not sufficient to overcome friction. Worm-and-gear sets that do lock are called **self locking**, which can be used to advantage, as for instance when it is desired to set the position of a mechanism by turning the worm and then have the mechanism hold that position. An example is the machine head found on some types of stringed instruments.

If the gear in a worm-and-gear set is an ordinary helical gear only a single point of contact will be achieved. If medium to high power transmission is desired, the tooth shape of the gear is modified to achieve more intimate contact by making both gears partially envelop each other. This is done by making both concave and joining them at a saddle point; this is called a **cone-drive**.

Worm gears can be right or left-handed following the long established practice for screw threads.

Non-circular

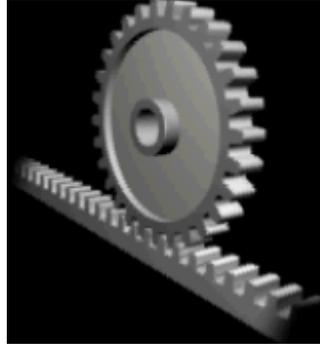


Non-circular gears

Non-circular gears are designed for special purposes. While a regular gear is optimized to transmit torque to another engaged member with minimum noise and wear and maximum

efficiency, a non-circular gear's main objective might be ratio variations, axle displacement oscillations and more. Common applications include textile machines, potentiometers and continuously variable transmissions.

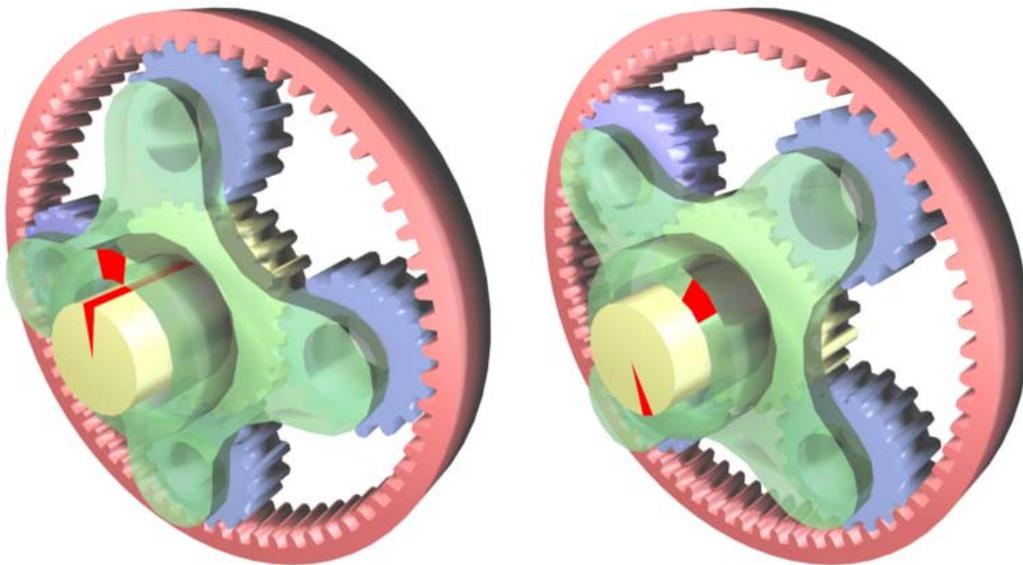
Rack and pinion



Rack and pinion gearing

A rack is a toothed bar or rod that can be thought of as a sector gear with an infinitely large radius of curvature. Torque can be converted to linear force by meshing a rack with a pinion: the pinion turns; the rack moves in a straight line. Such a mechanism is used in automobiles to convert the rotation of the steering wheel into the left-to-right motion of the tie rod(s). Racks also feature in the theory of gear geometry, where, for instance, the tooth shape of an interchangeable set of gears may be specified for the rack (infinite radius), and the tooth shapes for gears of particular actual radii then derived from that. The rack and pinion gear type is employed in a rack railway.

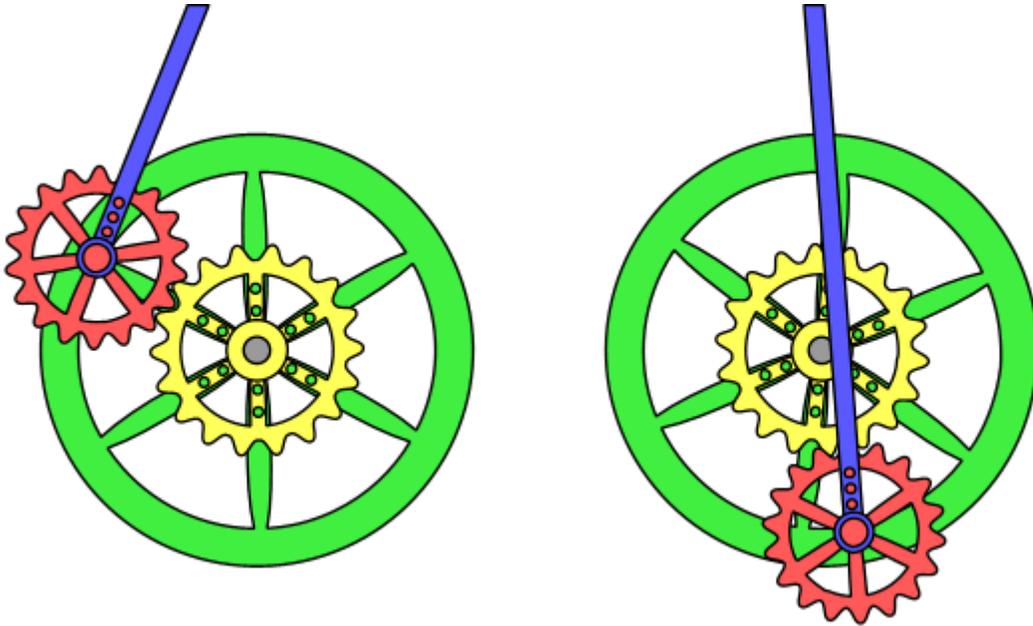
Epicyclic



Epicyclic gearing

In epicyclic gearing one or more of the gear axes moves. Examples are sun and planet gearing and mechanical differentials.

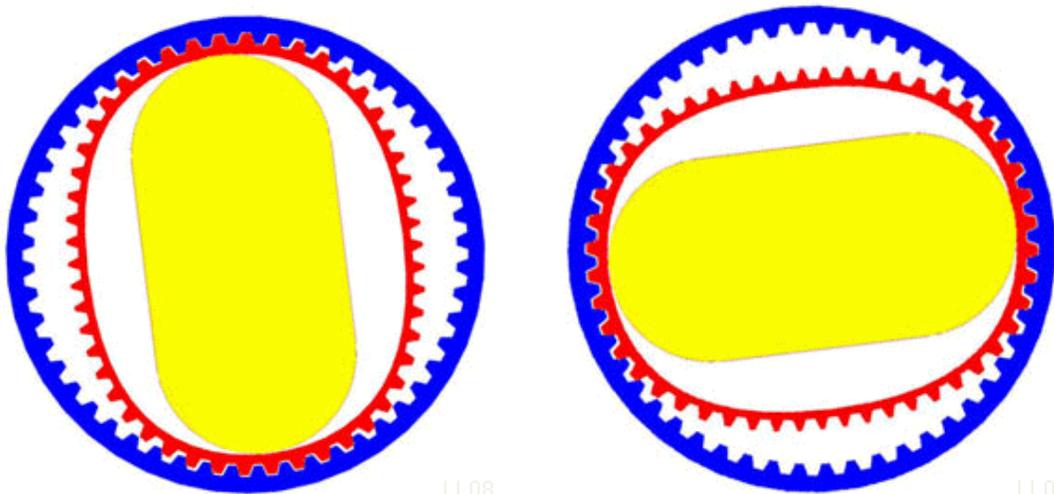
Sun and planet



Sun (yellow) and planet (red) gearing

Sun and planet gearing was a method of converting reciprocal motion into rotary motion in steam engines. It played an important role in the Industrial Revolution. The Sun is yellow, the planet red, the reciprocating crank is blue, the flywheel is green and the driveshaft is grey.

Harmonic drive



Harmonic drive gearing

A *harmonic drive* is a specialized proprietary gearing mechanism.

Cage gear

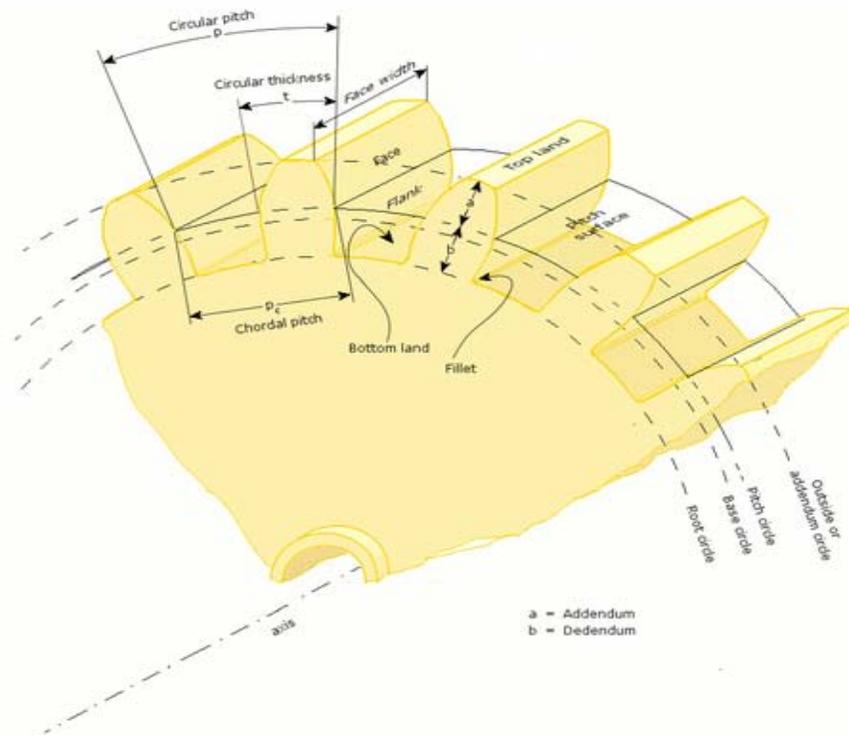


Cage gear in Pantigo Windmill, Long Island

A *cage gear*, also called a *lantern gear* or *lantern pinion* has cylindrical rods for teeth, parallel to the axle and arranged in a circle around it, much as the bars on a round bird cage or lantern. The assembly is held together by disks at either end into which the tooth rods and axle are set.

Nomenclature

General nomenclature



Rotational frequency, n

Measured in rotation over time, such as RPM.

Angular frequency, ω

Measured in radians per second. $1RPM = \pi / 30$ rad/second

Number of teeth, N

How many teeth a gear has, an integer. In the case of worms, it is the number of thread starts that the worm has.

Gear, wheel

The larger of two interacting gears or a gear on its own.

Pinion

The smaller of two interacting gears.

Path of contact

Path followed by the point of contact between two meshing gear teeth.

Line of action, pressure line

Line along which the force between two meshing gear teeth is directed. It has the same direction as the force vector. In general, the line of action changes from moment to moment during the period of engagement of a pair of teeth. For involute gears, however, the tooth-to-tooth force is always directed along the same line—that is, the line of action is constant. This implies that for involute gears the path of contact is also a straight line, coincident with the line of action—as is indeed the case.

Axis

Axis of revolution of the gear; center line of the shaft.

Pitch point, p

Point where the line of action crosses a line joining the two gear axes.

Pitch circle, pitch line

Circle centered on and perpendicular to the axis, and passing through the pitch point. A predefined diametral position on the gear where the circular tooth thickness, pressure angle and helix angles are defined.

Pitch diameter, d

A predefined diametral position on the gear where the circular tooth thickness, pressure angle and helix angles are defined. The standard pitch diameter is a basic dimension and cannot be measured, but is a location where other measurements are made. Its value is based on the number of teeth, the normal module (or normal diametral pitch), and the helix angle. It is calculated as:

$$d = \frac{Nm_n}{\cos\psi} \text{ in metric units or } d = \frac{N}{P_d \cos\psi} \text{ in imperial units.}$$

Module, m

A scaling factor used in metric gears with units in millimeters whose effect is to enlarge the gear tooth size as the module increases and reduce the size as the module decreases. Module can be defined in the normal (m_n), the transverse (m_t), or the axial planes (m_a) depending on the design approach employed and the type of gear being designed. Module is typically an input value into the gear design and is seldom calculated.

Operating pitch diameters

Diameters determined from the number of teeth and the center distance at which gears operate. Example for pinion:

$$d_w = \frac{2a}{u + 1} = \frac{2a}{\frac{z_2}{z_1} + 1}.$$

Pitch surface

In cylindrical gears, cylinder formed by projecting a pitch circle in the axial direction. More generally, the surface formed by the sum of all the pitch circles as one moves along the axis. For bevel gears it is a cone.

Angle of action

Angle with vertex at the gear center, one leg on the point where mating teeth first make contact, the other leg on the point where they disengage.

Arc of action

Segment of a pitch circle subtended by the angle of action.

Pressure angle, θ

The complement of the angle between the direction that the teeth exert force on each other, and the line joining the centers of the two gears. For involute gears, the teeth always exert force along the line of action, which, for involute gears, is a straight line; and thus, for involute gears, the pressure angle is constant.

Outside diameter, D_o

Diameter of the gear, measured from the tops of the teeth.

Root diameter

Diameter of the gear, measured at the base of the tooth.

Addendum, a

Radial distance from the pitch surface to the outermost point of the tooth. $a = (D_o - D) / 2$

Dedendum, b

Radial distance from the depth of the tooth trough to the pitch surface. $b = (D - \text{rootdiameter}) / 2$

Whole depth, h_t

The distance from the top of the tooth to the root; it is equal to addendum plus dedendum or to working depth plus clearance.

Clearance

Distance between the root circle of a gear and the addendum circle of its mate.

Working depth

Depth of engagement of two gears, that is, the sum of their operating addendums.

Circular pitch, p

Distance from one face of a tooth to the corresponding face of an adjacent tooth on the same gear, measured along the pitch circle.

Diametral pitch, p_d

Ratio of the number of teeth to the pitch diameter. Could be measured in teeth per inch or teeth per centimeter.

Base circle

In involute gears, where the tooth profile is the involute of the base circle. The radius of the base circle is somewhat smaller than that of the pitch circle.

Base pitch, normal pitch, p_b

In involute gears, distance from one face of a tooth to the corresponding face of an adjacent tooth on the same gear, measured along the base circle.

Interference

Contact between teeth other than at the intended parts of their surfaces.

Interchangeable set

A set of gears, any of which will mate properly with any other.

Helical gear nomenclature

Helix angle, ψ

Angle between a tangent to the helix and the gear axis. It is zero in the limiting case of a spur gear, albeit it can be considered as the hypotenuse angle as well.

Normal circular pitch, p_n

Circular pitch in the plane normal to the teeth.

Transverse circular pitch, p

Circular pitch in the plane of rotation of the gear. Sometimes just called "circular pitch". $p_n = p \cos(\psi)$

Several other helix parameters can be viewed either in the normal or transverse planes. The subscript n usually indicates the normal.

Worm gear nomenclature

Lead

Distance from any point on a thread to the corresponding point on the next turn of the same thread, measured parallel to the axis.

Linear pitch, p

Distance from any point on a thread to the corresponding point on the adjacent thread, measured parallel to the axis. For a single-thread worm, lead and linear pitch are the same.

Lead angle, λ

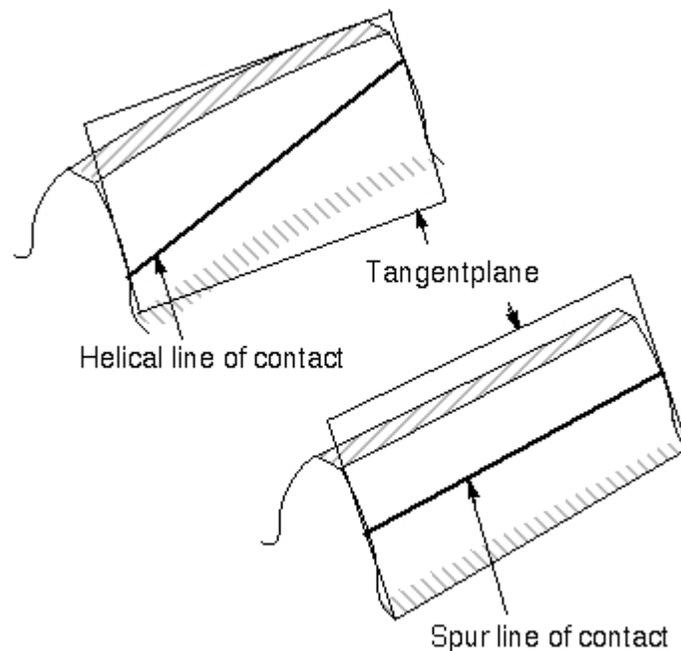
Angle between a tangent to the helix and a plane perpendicular to the axis. Note that it is the complement of the helix angle which is usually given for helical gears.

Pitch diameter, d_w

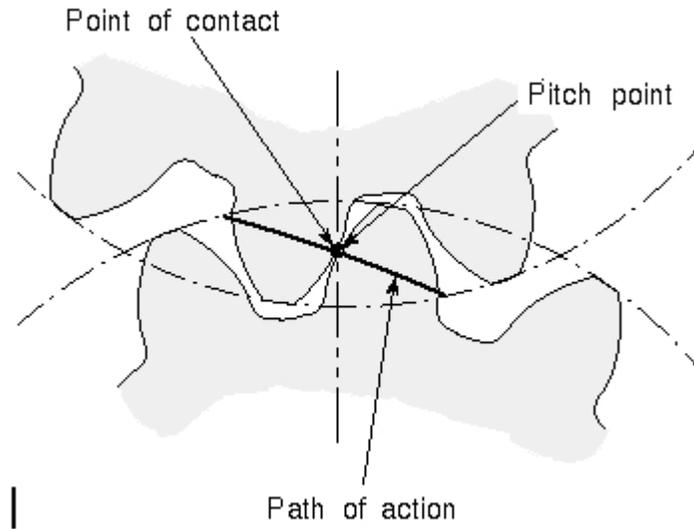
Same as described earlier in this list. Note that for a worm it is still measured in a plane perpendicular to the gear axis, not a tilted plane.

Subscript w denotes the worm, subscript g denotes the gear.

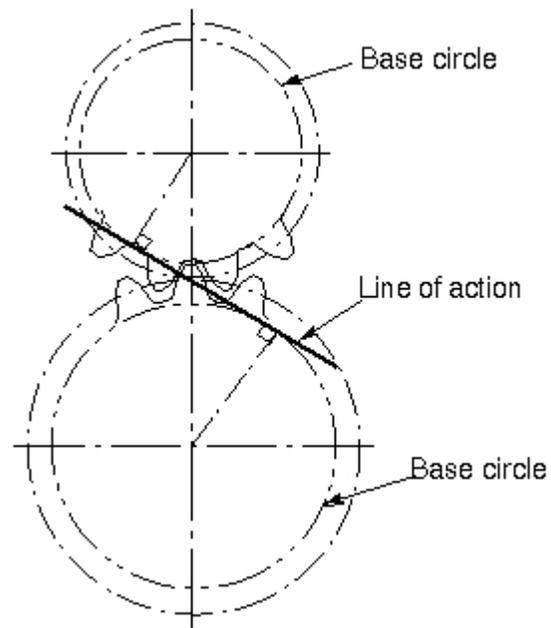
Tooth contact nomenclature



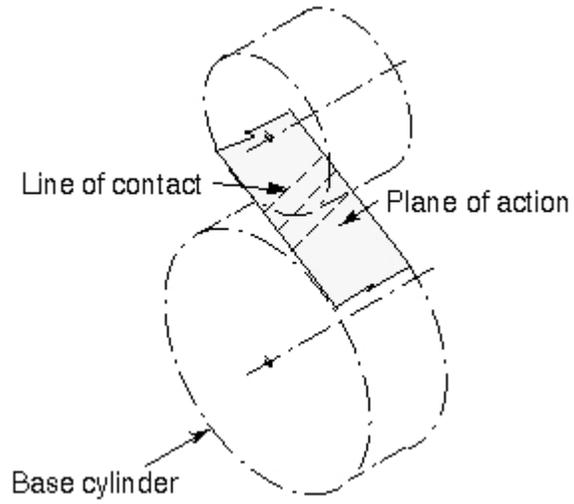
Line of contact



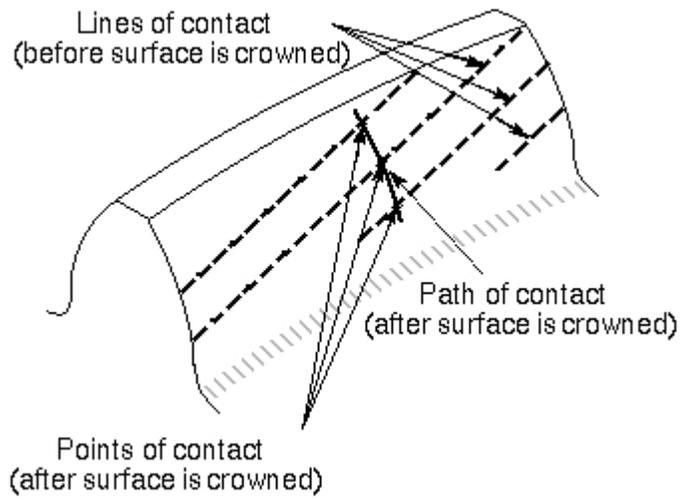
Path of action



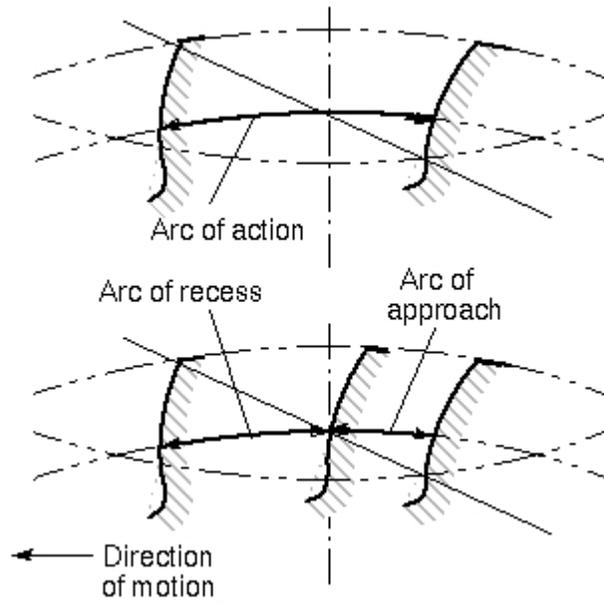
Line of action



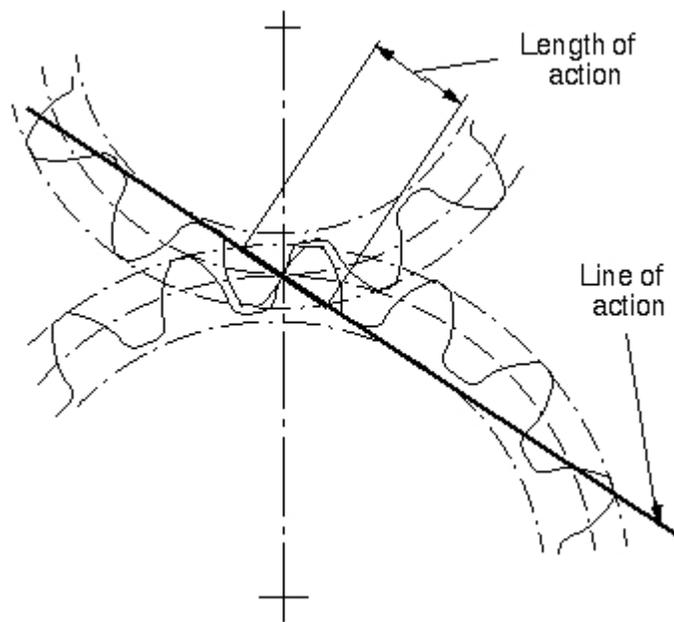
Plane of action



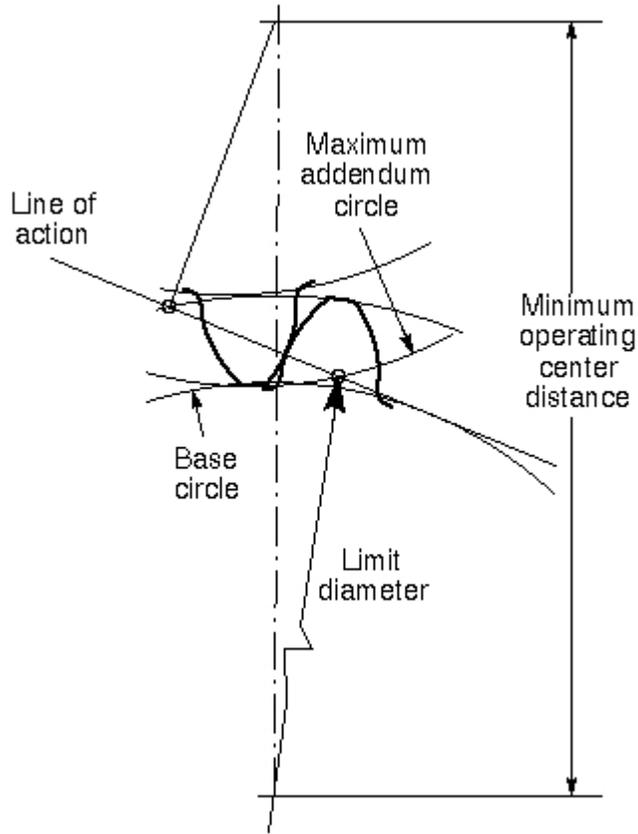
Lines of contact (helical gear)



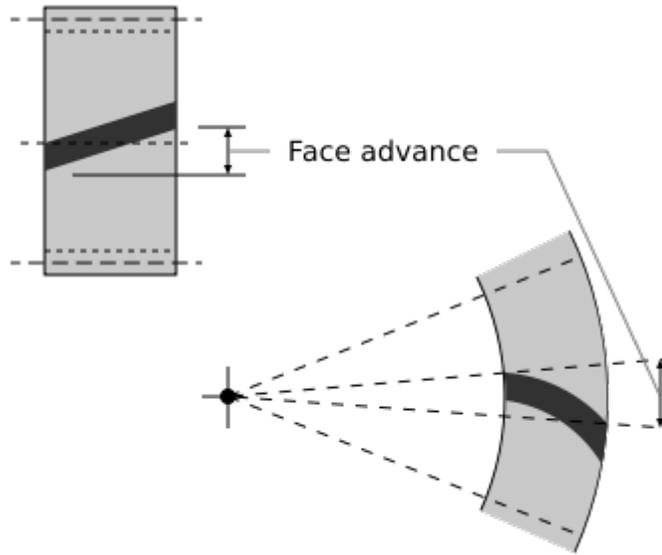
Arc of action



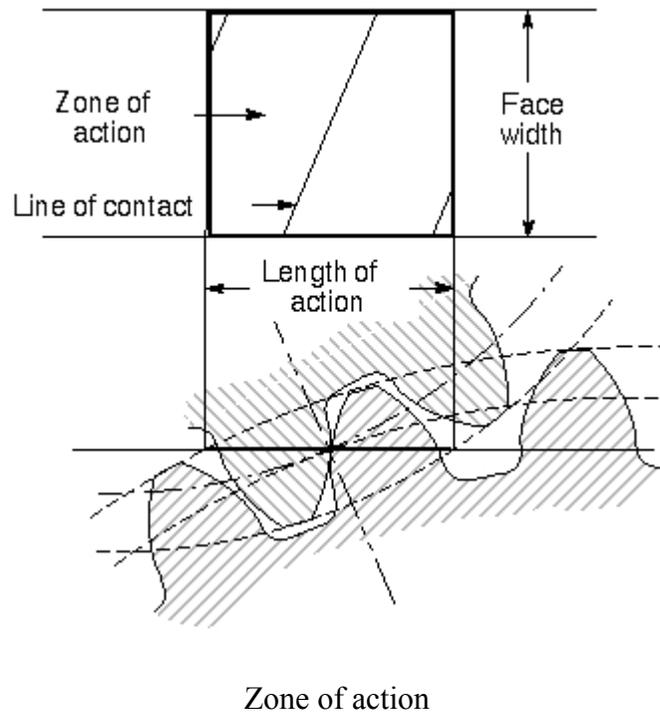
Length of action



Limit diameter



Face advance



Point of contact

Any point at which two tooth profiles touch each other.

Line of contact

A line or curve along which two tooth surfaces are tangent to each other.

Path of action

The locus of successive contact points between a pair of gear teeth, during the phase of engagement. For conjugate gear teeth, the path of action passes through the pitch point. It is the trace of the surface of action in the plane of rotation.

Line of action

The path of action for involute gears. It is the straight line passing through the pitch point and tangent to both base circles.

Surface of action

The imaginary surface in which contact occurs between two engaging tooth surfaces. It is the summation of the paths of action in all sections of the engaging teeth.

Plane of action

The surface of action for involute, parallel axis gears with either spur or helical teeth. It is tangent to the base cylinders.

Zone of action (contact zone)

For involute, parallel-axis gears with either spur or helical teeth, is the rectangular area in the plane of action bounded by the length of action and the effective face width.

Path of contact

The curve on either tooth surface along which theoretical single point contact occurs during the engagement of gears with crowned tooth surfaces or gears that normally engage with only single point contact.

Length of action

The distance on the line of action through which the point of contact moves during the action of the tooth profile.

Arc of action, Q_t

The arc of the pitch circle through which a tooth profile moves from the beginning to the end of contact with a mating profile.

Arc of approach, Q_a

The arc of the pitch circle through which a tooth profile moves from its beginning of contact until the point of contact arrives at the pitch point.

Arc of recess, Q_r

The arc of the pitch circle through which a tooth profile moves from contact at the pitch point until contact ends.

Contact ratio, m_c, ϵ

The number of angular pitches through which a tooth surface rotates from the beginning to the end of contact. In a simple way, it can be defined as a measure of the average number of teeth in contact during the period in which a tooth comes and goes out of contact with the mating gear.

Transverse contact ratio, m_p, ϵ_α

The contact ratio in a transverse plane. It is the ratio of the angle of action to the angular pitch. For involute gears it is most directly obtained as the ratio of the length of action to the base pitch.

Face contact ratio, m_F, ϵ_β

The contact ratio in an axial plane, or the ratio of the face width to the axial pitch. For bevel and hypoid gears it is the ratio of face advance to circular pitch.

Total contact ratio, m_t, ϵ_γ

The sum of the transverse contact ratio and the face contact ratio.

$$\epsilon_\gamma = \epsilon_\alpha + \epsilon_\beta$$

$$m_t = m_p + m_F$$

Modified contact ratio, m_o

For bevel gears, the square root of the sum of the squares of the transverse and face contact ratios.

$$m_o = (m_p^2 + m_F^2)^{0.5}$$

Limit diameter

Diameter on a gear at which the line of action intersects the maximum (or minimum for internal pinion) addendum circle of the mating gear. This is also referred to as the start of active profile, the start of contact, the end of contact, or the end of active profile.

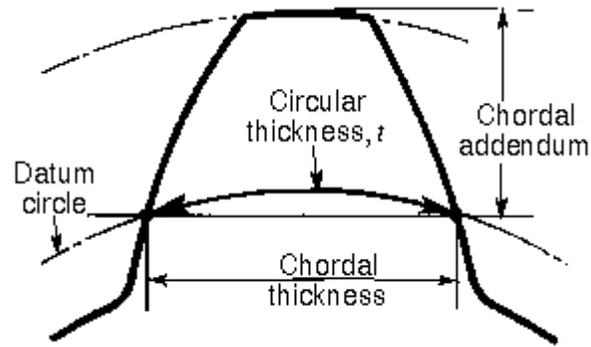
Start of active profile (SAP)

Intersection of the limit diameter and the involute profile.

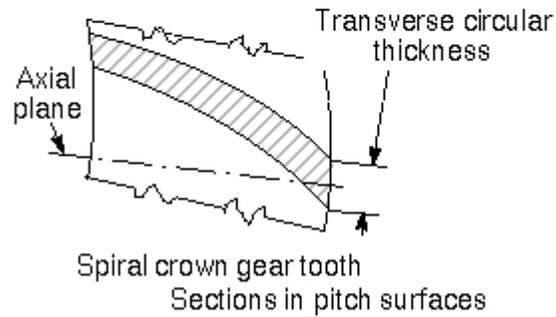
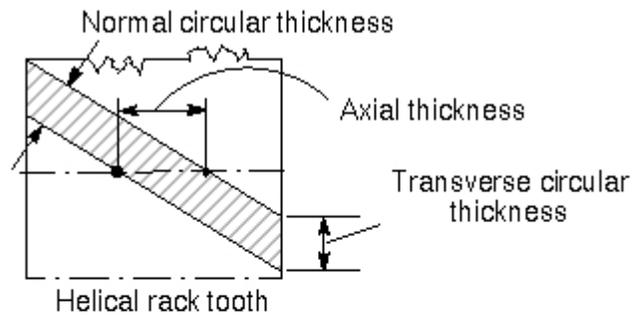
Face advance

Distance on a pitch circle through which a helical or spiral tooth moves from the position at which contact begins at one end of the tooth trace on the pitch surface to the position where contact ceases at the other end.

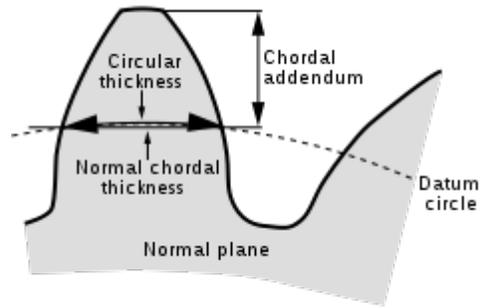
Tooth thickness nomenclature



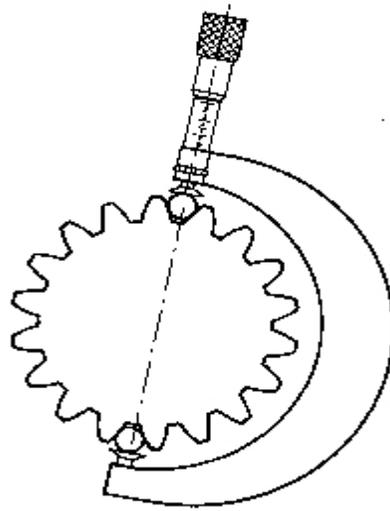
Tooth thickness



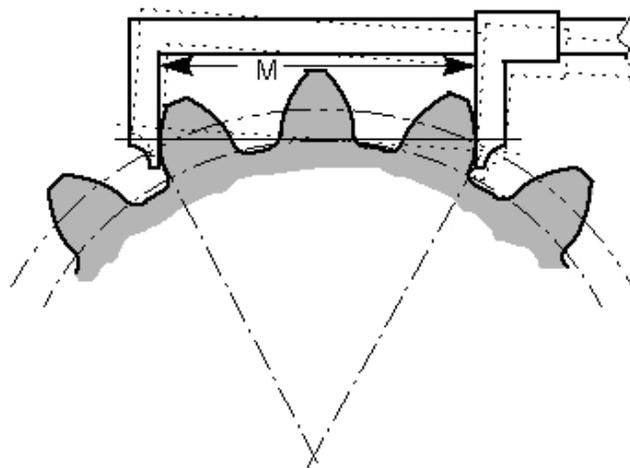
Thickness relationships



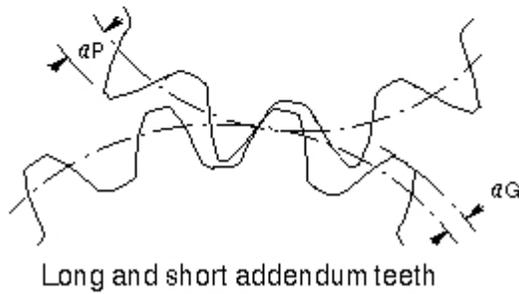
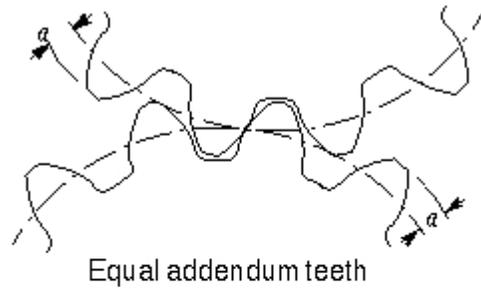
Chordal thickness



Tooth thickness measurement over pins



Span measurement



Long and short addendum teeth

Circular thickness

Length of arc between the two sides of a gear tooth, on the specified datum circle.

Transverse circular thickness

Circular thickness in the transverse plane.

Normal circular thickness

Circular thickness in the normal plane. In a helical gear it may be considered as the length of arc along a normal helix.

Axial thickness

In helical gears and worms, tooth thickness in an axial cross section at the standard pitch diameter.

Base circular thickness

In involute teeth, length of arc on the base circle between the two involute curves forming the profile of a tooth.

Normal chordal thickness

Length of the chord that subtends a circular thickness arc in the plane normal to the pitch helix. Any convenient measuring diameter may be selected, not necessarily the standard pitch diameter.

Chordal addendum (chordal height)

Height from the top of the tooth to the chord subtending the circular thickness arc. Any convenient measuring diameter may be selected, not necessarily the standard pitch diameter.

Profile shift

Displacement of the basic rack datum line from the reference cylinder, made non-dimensional by dividing by the normal module. It is used to specify the tooth thickness, often for zero backlash.

Rack shift

Displacement of the tool datum line from the reference cylinder, made non-dimensional by dividing by the normal module. It is used to specify the tooth thickness.

Measurement over pins

Measurement of the distance taken over a pin positioned in a tooth space and a reference surface. The reference surface may be the reference axis of the gear, a datum surface or either one or two pins positioned in the tooth space or spaces opposite the first. This measurement is used to determine tooth thickness.

Span measurement

Measurement of the distance across several teeth in a normal plane. As long as the measuring device has parallel measuring surfaces that contact on an unmodified portion of the involute, the measurement will be along a line tangent to the base cylinder. It is used to determine tooth thickness.

Modified addendum teeth

Teeth of engaging gears, one or both of which have non-standard addendum.

Full-depth teeth

Teeth in which the working depth equals 2.000 divided by the normal diametral pitch.

Stub teeth

Teeth in which the working depth is less than 2.000 divided by the normal diametral pitch.

Equal addendum teeth

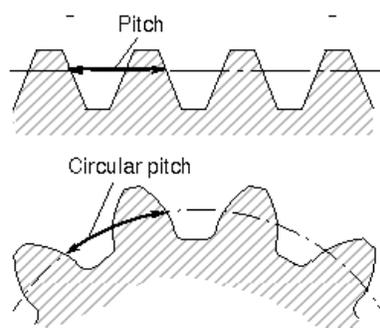
Teeth in which two engaging gears have equal addendums.

Long and short-addendum teeth

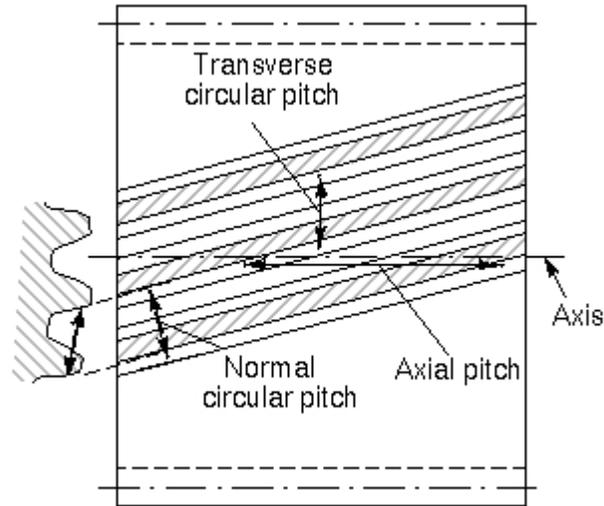
Teeth in which the addendums of two engaging gears are unequal.

Pitch nomenclature

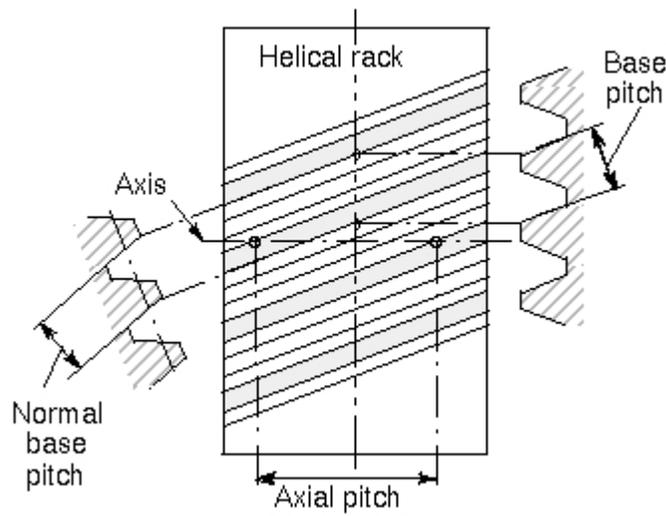
Pitch is the distance between a point on one tooth and the corresponding point on an adjacent tooth. It is a dimension measured along a line or curve in the transverse, normal, or axial directions. The use of the single word *pitch* without qualification may be ambiguous, and for this reason it is preferable to use specific designations such as transverse circular pitch, normal base pitch, axial pitch.



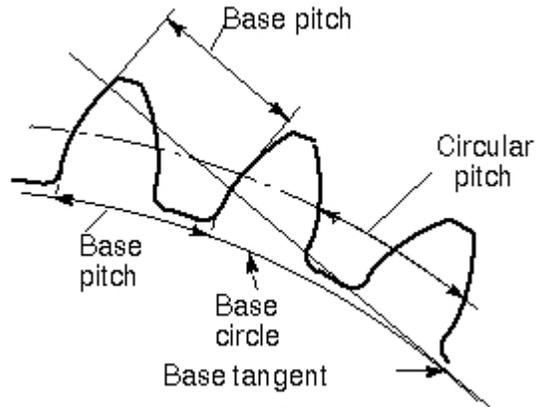
Pitch



Tooth pitch



Base pitch relationships



Principal pitches

Circular pitch, p

Arc distance along a specified pitch circle or pitch line between corresponding profiles of adjacent teeth.

Transverse circular pitch, p_t

Circular pitch in the transverse plane.

Normal circular pitch, p_n, p_e

Circular pitch in the normal plane, and also the length of the arc along the normal pitch helix between helical teeth or threads.

Axial pitch, p_x

Linear pitch in an axial plane and in a pitch surface. In helical gears and worms, axial pitch has the same value at all diameters. In gearing of other types, axial pitch may be confined to the pitch surface and may be a circular measurement. The term axial pitch is preferred to the term linear pitch. The axial pitch of a helical worm and the circular pitch of its worm gear are the same.

Normal base pitch, p_N, p_{bn}

An involute helical gear is the base pitch in the normal plane. It is the normal distance between parallel helical involute surfaces on the plane of action in the normal plane, or is the length of arc on the normal base helix. It is a constant distance in any helical involute gear.

Transverse base pitch, p_b, p_{bt}

In an involute gear, the pitch on the base circle or along the line of action. Corresponding sides of involute gear teeth are parallel curves, and the base pitch is the constant and fundamental distance between them along a common normal in a transverse plane.

Diametral pitch (transverse), P_d

Ratio of the number of teeth to the standard pitch diameter in inches.

$$P_d = \frac{N}{d} = \frac{25.4}{m} = \frac{\pi}{p}$$

Normal diametral pitch, P_{nd}

Value of diametral pitch in a normal plane of a helical gear or worm.

$$P_{nd} = \frac{P_d}{\cos \psi}$$

Angular pitch, θ_N , τ

Angle subtended by the circular pitch, usually expressed in radians.

$$\tau = \frac{360}{z} \text{ degrees or } \frac{2\pi}{z} \text{ radians}$$

Backlash

Backlash is the error in motion that occurs when gears change direction. It exists because there is always some gap between the trailing face of the driving tooth and the leading face of the tooth behind it on the driven gear, and that gap must be closed before force can be transferred in the new direction. The term "backlash" can also be used to refer to the size of the gap, not just the phenomenon it causes; thus, one could speak of a pair of gears as having, for example, "0.1 mm of backlash." A pair of gears could be designed to have zero backlash, but this would presuppose perfection in manufacturing, uniform thermal expansion characteristics throughout the system, and no lubricant. Therefore, gear pairs are designed to have some backlash. It is usually provided by reducing the tooth thickness of each gear by half the desired gap distance. In the case of a large gear and a small pinion, however, the backlash is usually taken entirely off the gear and the pinion is given full sized teeth. Backlash can also be provided by moving the gears farther apart.

For situations, such as instrumentation and control, where precision is important, backlash can be minimised through one of several techniques. For instance, the gear can be split along a plane perpendicular to the axis, one half fixed to the shaft in the usual manner, the other half placed alongside it, free to rotate about the shaft, but with springs between the two halves providing relative torque between them, so that one achieves, in effect, a single gear with expanding teeth. Another method involves tapering the teeth in the axial direction and providing for the gear to be slid in the axial direction to take up slack.

Shifting of gears

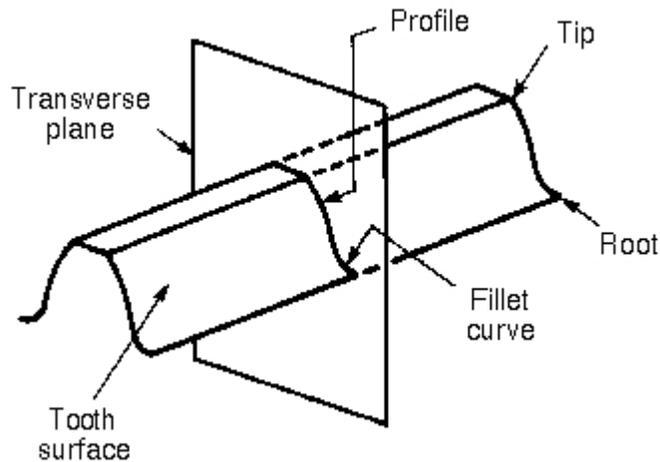
In some machines (e.g., automobiles) it is necessary to alter the gear ratio to suit the task. There are several methods of accomplishing this. For example:

- Manual transmission
- Automatic transmission
- Deraillleur gears which are actually sprockets in combination with a roller chain
- Hub gears (also called epicyclic gearing or sun-and-planet gears)

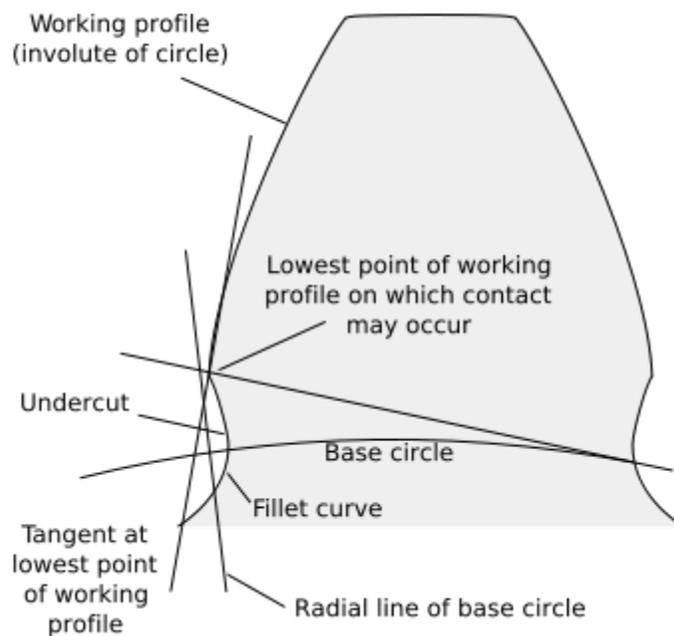
There are several outcomes of gear shifting in motor vehicles. In the case of vehicle noise emissions, there are higher sound levels emitted when the vehicle is engaged in lower gears. The design life of the lower ratio gears is shorter so cheaper gears may be used (i.e.

spur for 1st and reverse) which tends to generate more noise due to smaller overlap ratio and a lower mesh stiffness etc than the helical gears used for the high ratios. This fact has been utilized in analyzing vehicle generated sound since the late 1960s, and has been incorporated into the simulation of urban roadway noise and corresponding design of urban noise barriers along roadways.

Tooth profile



Profile of a spur gear



Undercut

A profile is one side of a tooth in a cross section between the outside circle and the root circle. Usually a profile is the curve of intersection of a tooth surface and a plane or surface normal to the pitch surface, such as the transverse, normal, or axial plane.

The fillet curve (root fillet) is the concave portion of the tooth profile where it joins the bottom of the tooth space.²

As mentioned in the beginning, the attainment of a non fluctuating velocity ratio is dependent on the profile of the teeth. Friction and wear between two gears is also dependent on the tooth profile. There are a great many tooth profiles that will give a constant velocity ratio, and in many cases, given an arbitrary tooth shape, it is possible to develop a tooth profile for the mating gear that will give a constant velocity ratio. However, two constant velocity tooth profiles have been by far the most commonly used in modern times. They are the cycloid and the involute. The cycloid was more common until the late 1800s; since then the involute has largely superseded it, particularly in drive train applications. The cycloid is in some ways the more interesting and flexible shape; however the involute has two advantages: it is easier to manufacture, and it permits the center to center spacing of the gears to vary over some range without ruining the constancy of the velocity ratio. Cycloidal gears only work properly if the center spacing is exactly right. Cycloidal gears are still used in mechanical clocks.

An undercut is a condition in generated gear teeth when any part of the fillet curve lies inside of a line drawn tangent to the working profile at its point of juncture with the fillet. Undercut may be deliberately introduced to facilitate finishing operations. With undercut the fillet curve intersects the working profile. Without undercut the fillet curve and the working profile have a common tangent.

Gear materials



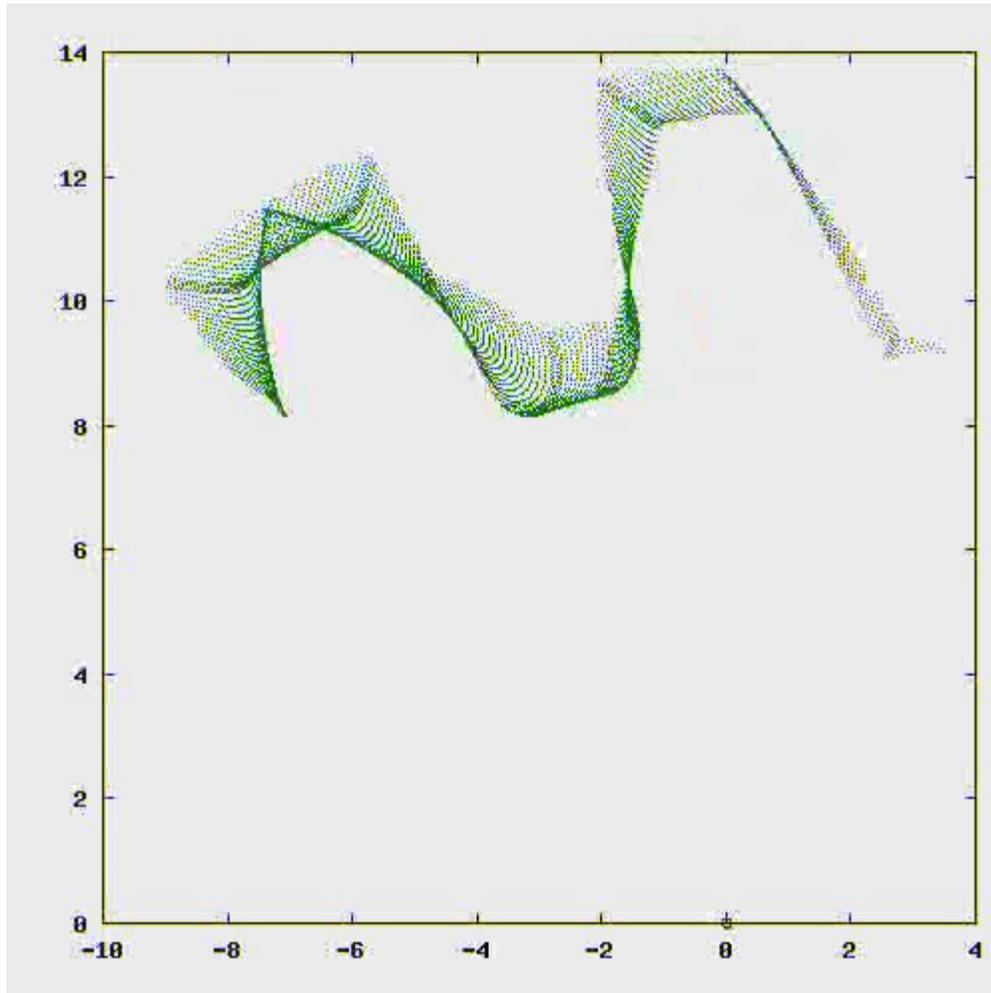
Wooden gears of a historic windmill

Numerous nonferrous alloys, cast irons, powder-metallurgy and even plastics are used in the manufacture of gears. However steels are most commonly used because of their high strength to weight ratio and low cost. Plastic is commonly used where cost or weight is a concern. A properly designed plastic gear can replace steel in many cases because it has many desirable properties, including dirt tolerance, low speed meshing, and the ability to "skip" quite well. Manufacturers have employed plastic gears to make consumer items affordable in items like copy machines, optical storage devices, VCRs, cheap dynamos, consumer audio equipment, servo motors, and printers.

The module system

Countries which have adopted the metric system generally use the module system. As a result, the term module is usually understood to mean the pitch diameter in millimeters divided by the number of teeth. When the module is based upon inch measurements, it is known as the *English module* to avoid confusion with the metric module. Module is a direct dimension, whereas diametral pitch is an inverse dimension (like "threads per inch"). Thus, if the pitch diameter of a gear is 40 mm and the number of teeth 20, the module is 2, which means that there are 2 mm of pitch diameter for each tooth.

Manufacture



Gear Cutting simulation faster, high bitrate version.

Gears are most commonly produced via hobbing, but they are also shaped, broached, cast, and in the case of plastic gears, injection molded. For metal gears the teeth are usually heat treated to make them hard and more wear resistant while leaving the core soft and tough. For large gears that are prone to warp a quench press is used.

Inspection

Gear geometry can be inspected and verified using various methods such as industrial CT scanning, coordinate-measuring machines, white light scanner or laser scanning.

Particularly useful for plastic gears, industrial CT scanning can inspect internal geometry and imperfections such as porosity.

Gear model in modern physics

Modern physics adopted the gear model in different ways. In the nineteenth century, James Clerk Maxwell developed a model of electromagnetism in which magnetic field lines were rotating tubes of incompressible fluid. Maxwell used a gear wheel and called it an "idle wheel" to explain the electrical current as a rotation of particles in opposite directions to that of the rotating field lines.

More recently, quantum physics uses "quantum gears" in their model. A group of gears can serve as a model for several different systems, such as an artificially constructed nanomechanical device or a group of ring molecules.

The Three Wave Hypothesis compares the wave–particle duality to a bevel gear.

Chapter 2

Bevel Gear

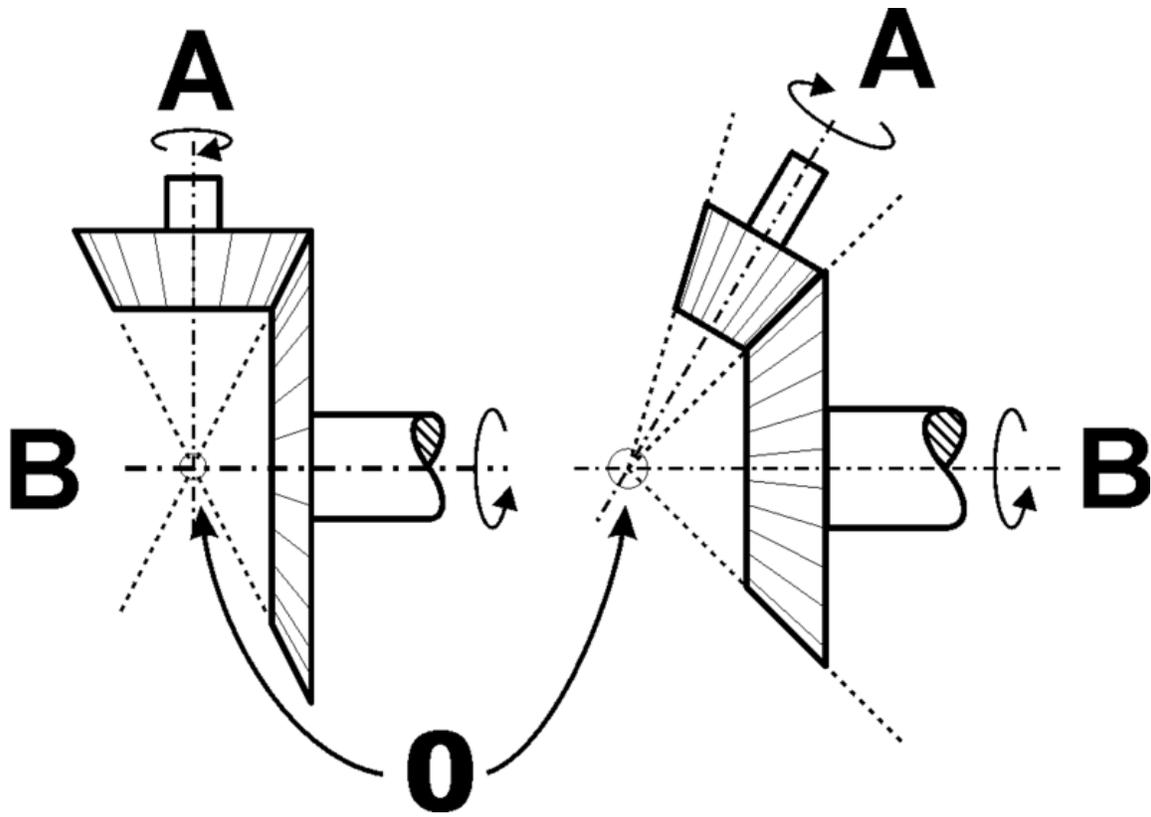
Bevel gears are gears where the axes of the two shafts intersect and the tooth-bearing faces of the gears themselves are conically shaped. Bevel gears are most often mounted on shafts that are 90 degrees apart, but can be designed to work at other angles as well. The pitch surface of bevel gears is a cone.



Bevel gear lifts floodgate by means of central screw.



Bevel gear on roller shutter door.



Independently from the operating angle, the gear axes must intersect (at the point O)



Bevel ring gear on the rear wheel of a shaft-driven bicycle



Spiral bevel gear - ZF Friedrichshafen

Introduction

Two important concepts in gearing are **pitch surface** and **pitch angle**. The pitch surface of a gear is the imaginary toothless surface that you would have by averaging out the peaks and valleys of the individual teeth. The pitch surface of an ordinary gear is the shape of a cylinder. The pitch angle of a gear is the angle between the face of the pitch surface and the axis.

The most familiar kinds of bevel gears have pitch angles of less than 90 degrees and therefore are cone-shaped. This type of bevel gear is called **external** because the gear teeth point outward. The pitch surfaces of meshed external bevel gears are coaxial with the gear shafts; the apexes of the two surfaces are at the point of intersection of the shaft axes.

Bevel gears that have pitch angles of greater than ninety degrees have teeth that point inward and are called **internal** bevel gears.

Bevel gears that have pitch angles of exactly 90 degrees have teeth that point outward parallel with the axis and resemble the points on a crown. That's why this type of bevel gear is called a **crown** gear.

Miter gears are mating bevel gears with equal numbers of teeth and with axes at right angles.

Skew bevel gears are those for which the corresponding crown gear has teeth that are straight and oblique.

Teeth

There are two issues regarding tooth shape. One is the cross-sectional profile of the individual tooth. The other is the line or curve on which the tooth is set on the face of the gear: in other words the line or curve along which the cross-sectional profile is projected to form the actual three-dimensional shape of the tooth. The primary effect of both the cross-sectional profile and the tooth line or curve is on the smoothness of operation of the gears. Some result in a smoother gear action than others.

Tooth line

The teeth on bevel gears can be straight, spiral or "zero".

Straight tooth lines

In **straight bevel gears** the teeth are straight and parallel to the generators of the cone. This is the simplest form of bevel gear. It resembles a spur gear, only conical rather than cylindrical. The gears in the floodgate picture are straight bevel gears. In straight, when each tooth engages it impacts the corresponding tooth and simply curving the gear teeth can solve the problem.

Spiral tooth lines

Spiral bevel gears have their teeth formed along spiral lines. They are somewhat analogous to cylindrical type helical gears in that the teeth are angled; however with spiral gears the teeth are also curved.

The advantage of the spiral tooth over the straight tooth is that they engage more gradually. The contact between the teeth starts at one end of the gear and then spreads across the whole tooth. This results in a less abrupt transfer of force when a new pair of teeth come in to play. With straight bevel gears, the abrupt tooth engagement causes noise, especially at high speeds, and impact stress on the teeth which makes them unable to take heavy loads at high speeds without breaking. For these reasons straight bevel gears are generally limited to use at linear speeds less than 1000 feet/min; or, for small gears, under 1000 r.p.m.

Zero tooth lines

Zero bevel gears are an intermediate type between straight and spiral bevel gears. Their teeth are curved, but not angled.

Applications

The bevel gear has many diverse applications such as locomotives, marine applications, automobiles, printing presses, cooling towers, power plants, steel plants, railway track inspection machines, etc.

For examples :

- Bevel gears are used in **differential drives**, which can transmit power to two axles spinning at different speeds, such as those on a cornering automobile.
- Bevel gears are used as the main mechanism for a **hand drill**. As the handle of the drill is turned in a vertical direction, the bevel gears change the rotation of the chuck to a horizontal rotation. The bevel gears in a hand drill have the added advantage of increasing the speed of rotation of the chuck and this makes it possible to drill a range of materials.
- The gears in a **bevel gear planer** permit minor adjustment during assembly and allow for some displacement due to deflection under operating loads without concentrating the load on the end of the tooth.
- Spiral bevel gears are important components on **rotorcraft** drive systems. These components are required to operate at high speeds, high loads, and for a large number of load cycles. In this application, spiral bevel gears are used to redirect the shaft from the horizontal gas turbine engine to the vertical rotor.



Bevel gears on grain mill at Dordrecht. Note wooden teeth inserts on one of the gears.

Advantages

- This gear makes it possible to change the operating angle.
- Differing of the number of teeth (effectively diameter) on each wheel allows mechanical advantage to be changed. By increasing or decreasing the ratio of teeth between the drive and driven wheels one may change the ratio of rotations between the two, meaning that the rotational drive and torque of the second wheel can be changed in relation to the first, with speed increasing and torque decreasing, or speed decreasing and torque increasing.

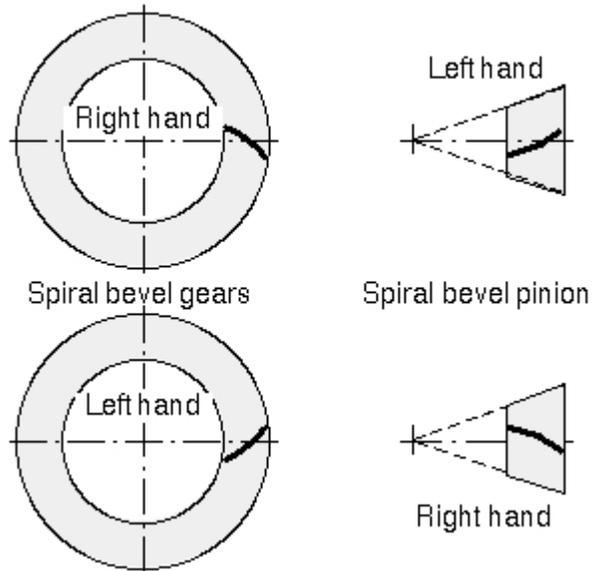
Disadvantages

- One wheel of such gear is designed to work with its complementary wheel and no other.
- Must be precisely mounted.
- The axes must be capable of supporting significant forces.

Chapter 3

Spiral Bevel Gear and Herringbone Gear

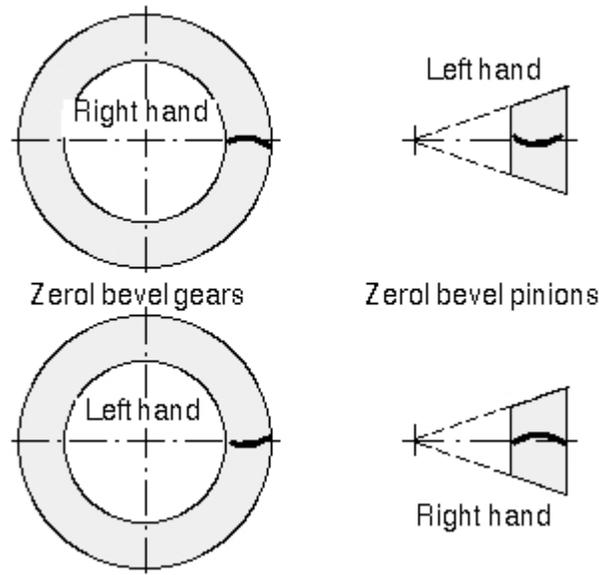
Spiral bevel gear



Spiral bevel gears

Spiral bevel pinion

Spiral bevel handedness



Zerol handedness

A **spiral bevel gear** is a bevel gear with helical teeth. The main application of this is in a vehicle differential, where the direction of drive from the drive shaft must be turned 90 degrees to drive the wheels. The helical design produces less vibration and noise than conventional straight-cut or spur-cut gear with straight teeth.

A spiral bevel gear set should always be replaced in pairs i.e. both the left hand and right hand gears should be replaced together since the gears are manufactured and lapped in pairs.

Handedness

A **right hand** spiral bevel gear is one in which the outer half of a tooth is inclined in the clockwise direction from the axial plane through the midpoint of the tooth as viewed by an observer looking at the face of the gear.

A **left hand** spiral bevel gear is one in which the outer half of a tooth is inclined in the counterclockwise direction from the axial plane through the midpoint of the tooth as viewed by an observer looking at the face of the gear.

Note that a spiral bevel gear and pinion are always of opposite hand, including the case when the gear is internal.

Also note that the designations right hand and left hand are applied similarly to other types of bevel gear, hypoid gears, and oblique tooth face gears.

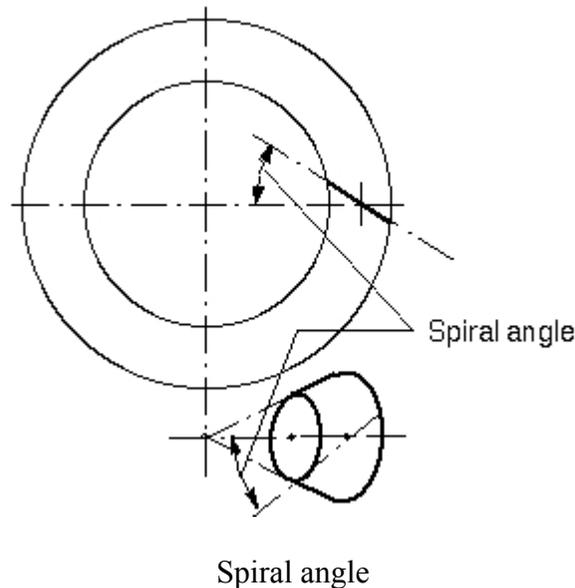
Hypoid gears

A **hypoid** is a type of spiral bevel gear whose axis does not intersect with the axis of the meshing gear. The shape of a hypoid gear is a revolved hyperboloid (that is, the pitch surface of the hypoid gear is a hyperbolic surface), whereas the shape of a spiral bevel gear is normally conical. The hypoid gear places the pinion off-axis to the crown wheel (ring gear) which allows the pinion to be larger in diameter and have more contact area. In hypoid gear design, the pinion and gear are practically always of opposite hand, and the spiral angle of the pinion is usually larger than that of the gear. The hypoid pinion is then larger in diameter than an equivalent bevel pinion.

A hypoid gear incorporates some sliding and can be considered halfway between a straight-cut gear and a worm gear. Special gear oils are required for hypoid gears because the sliding action requires effective lubrication under extreme pressure between the teeth.

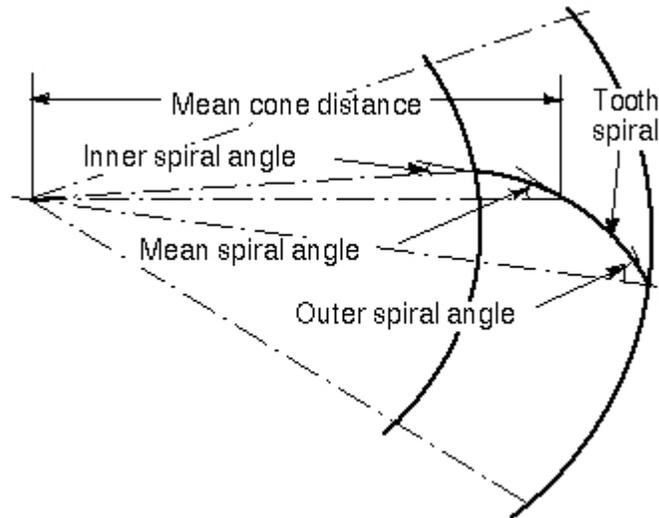
Hypoid gearings are used in power transmission products that are more efficient than conventional worm gearing.

Spiral angle



The spiral angle in a spiral bevel gear is the angle between the tooth trace and an element of the pitch cone, and corresponds to the helix angle in helical teeth. Unless otherwise specified, the term spiral angle is understood to be the mean spiral angle.

- Mean spiral angle is the specific designation for the spiral angle at the mean cone distance in a bevel gear.
- Outer spiral angle is the spiral angle of a bevel gear at the outer cone distance.
- Inner spiral angle is the spiral angle of a bevel gear at the inner cone distance.



Spiral angle relationships

Comparison of spiral bevel gears to hypoid gears

Hypoid gears are stronger, operate more quietly and can be used for higher reduction ratios, however they also have some sliding action along the teeth, which reduces mechanical efficiency, the energy losses being in the form of heat produced in the gear surfaces and the lubricating fluid.

In older automotive designs, hypoid gears were typically used in rear-drive automobile drivetrains, but modern designs have tended to substitute spiral bevel gears to increase driving efficiency.

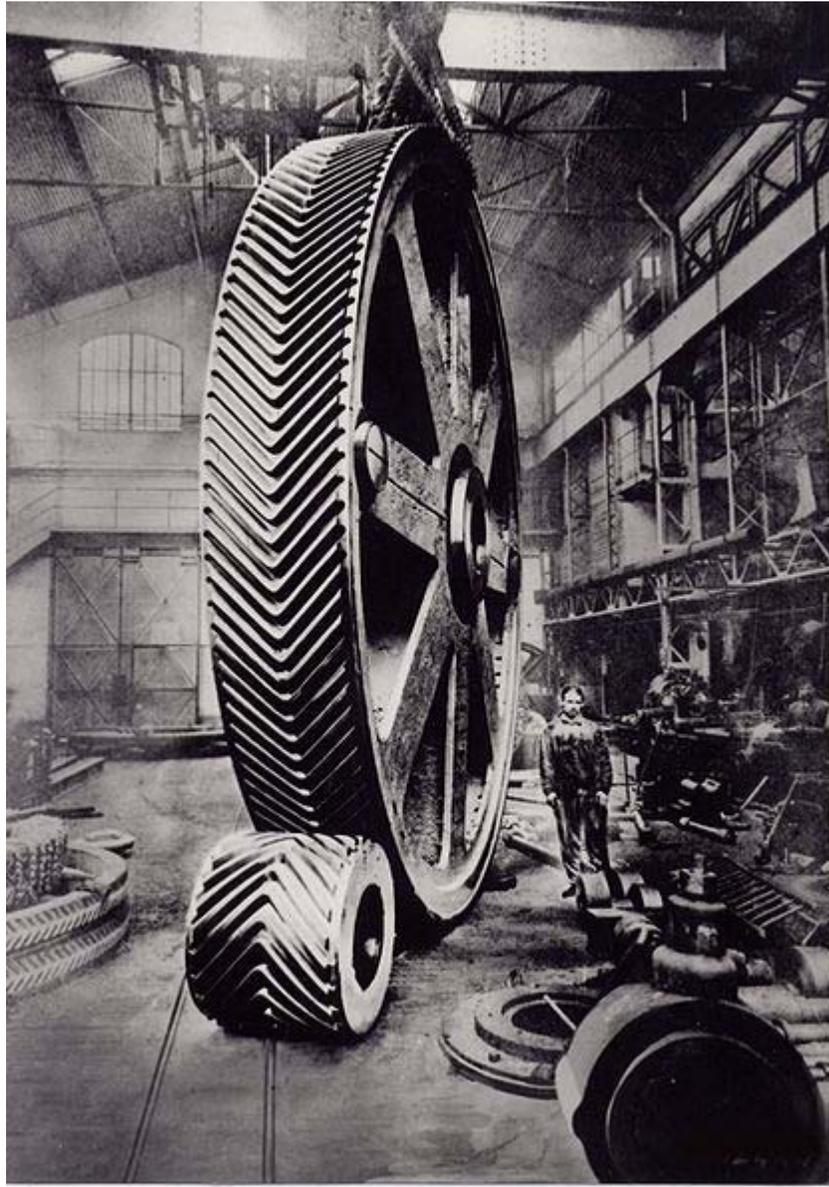
Hypoid gears are still common in larger trucks because they can transmit higher torque. A higher hypoid offset allows the gear to transmit higher torque. However increasing the hypoid offset results in reduction of mechanical efficiency and a consequent reduction in fuel economy. For practical purposes, it is often impossible to replace low efficiency hypoid gears with more efficient spiral bevel gears in automotive use because the spiral bevel gear would need a much larger diameter to transmit the same torque. Increasing the size of the drive axle gear would require an increase of the size of the gear housing and a reduction in the ground clearance.

Another advantage of hypoid gear is that the ring gear of the differential and the input pinion gear are both hypoid. In most passenger cars this allows the pinion to be offset to the bottom of the crown wheel. This provides for longer tooth contact and allows the shaft that drives the pinion to be lowered, reducing the "hump" intrusion in the passenger compartment floor. However, the greater the displacement of the input shaft axis from the crown wheel axis, the lower the mechanical efficiency.



Hypoid gear in a differential

Herringbone gear



A **herringbone gear**, also known as a **double helical gear**, is a special type of gear which is a side to side (not face to face) combination of two helical gears of opposite hands. Unlike helical gears they can sustain axial load smoothly. From the top the helical grooves of this gear looks like letter V.

Like helical gears, they have the advantage of transferring power smoothly as multiple gear teeth engage and disengage simultaneously. Their advantage over the helical gears is that the side-thrust of one half is balanced by that of the other half. This means that herringbone gears can be used in torque gearboxes without requiring a substantial thrust

bearing. Because of this herringbone gears were an important step in the introduction of the steam turbine to marine propulsion.

Precision herringbone gears are more difficult to manufacture than equivalent spur or helical gears and consequently are more expensive. They are used in heavy machinery.

Where the oppositely angled teeth meet in the middle of a herringbone gear, the alignment may be such that tooth tip meets tooth tip, or the alignment may be staggered, so that tooth tip meets tooth trough. The latter alignment is the unique defining characteristic of a Wuest type herringbone gear, named after its inventor.

With the older method of fabrication, herringbone gears had a central channel separating the two oppositely-angled courses of teeth. This was necessary to permit the shaving tool to run out of the groove. The development of the Sykes gear shaper made it possible to have continuous teeth, with no central gap. After the W.E. Sykes and Farrel Gear Machine companies dissolved in 1983-84 there are no current production machines that have this ability. It is standard industry practice to obtain an older machine and rebuild it if necessary to create this unique type of gear. A disadvantage of the herringbone gear is that it cannot be cut by simple gear hobbing machines, as the cutter would run into the other half of the gear. Solutions to this have included assembling small gears by stacking two helical gears together, cutting the gears with a central groove to provide clearance, and (particularly in the early days) by casting the gears to an accurate pattern and without further machining.

The logo of the car maker Citroën is a graphic representation of a herringbone gear, it comes from Andre Citroën's early involvement in the manufacture of these gears.

Chapter 4

Worm Drive

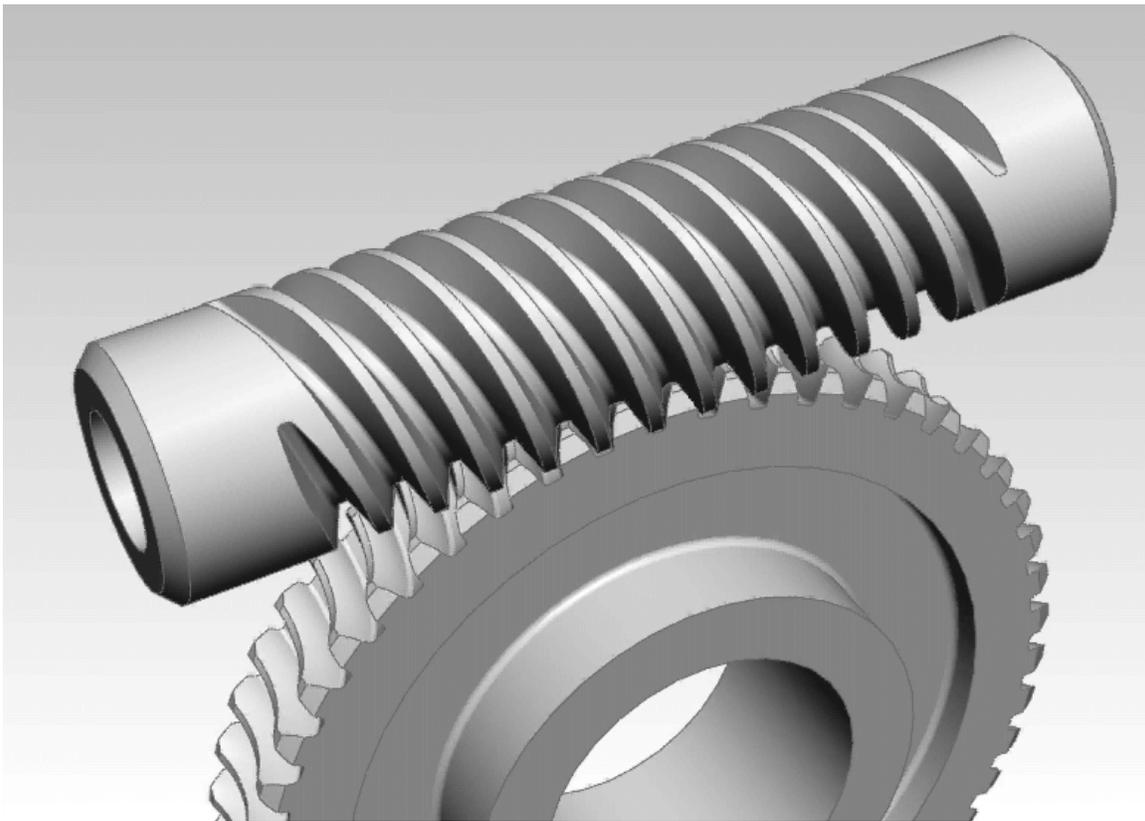


Worm and worm gear

A **worm drive** is a gear arrangement in which a **worm** (which is a gear in the form of a screw) meshes with a **worm gear** (which is similar in appearance to a spur gear, and is also called a **worm wheel**). The terminology is often confused by imprecise use of the term *worm gear* to refer to the worm, the worm gear, or the worm drive as a unit.

Like other gear arrangements, a worm drive can reduce rotational speed or allow higher torque to be transmitted. The image shows a section of a gear box with a worm gear being driven by a worm. A worm is an example of a screw, one of the six simple machines.

Explanation



Worm gear with 4-start worm

A gearbox designed using a worm and worm-wheel will be considerably smaller than one made from plain spur gears and has its drive axes at 90° to each other. With a *single start* worm, for each 360° turn of the worm, the worm-gear advances only one tooth of the gear. Therefore, regardless of the worm's size (sensible engineering limits notwithstanding), the gear ratio is the "*size of the worm gear - to - 1*". Given a single start worm, a 20 tooth worm gear will reduce the speed by the ratio of 20:1. With spur gears, a gear of 12 teeth (the smallest size permissible, if designed to good engineering practices) would have to be matched with a 240 tooth gear to achieve the same ratio of 20:1. Therefore, if the diametrical pitch (DP) of each gear was the same, then, in terms of the

physical size of the 240 tooth gear to that of the 20 tooth gear, the worm arrangement is considerably smaller in volume.



A double bass features worm gears as tuning mechanisms

Types

There are three different types of gears that can go in a worm drive.

The first are *non-throated* worm gears. These don't have a *throat*, or groove, machined around the circumference around either the worm or worm wheel. The second are single-throated worm gears, in which the worm wheel is throated. The final type are double-throated worm gears, which have both gears throated. This type of gearing can support the highest loading.

An enveloping (hourglass) worm has one or more teeth and increases in diameter from its middle portion toward both ends.

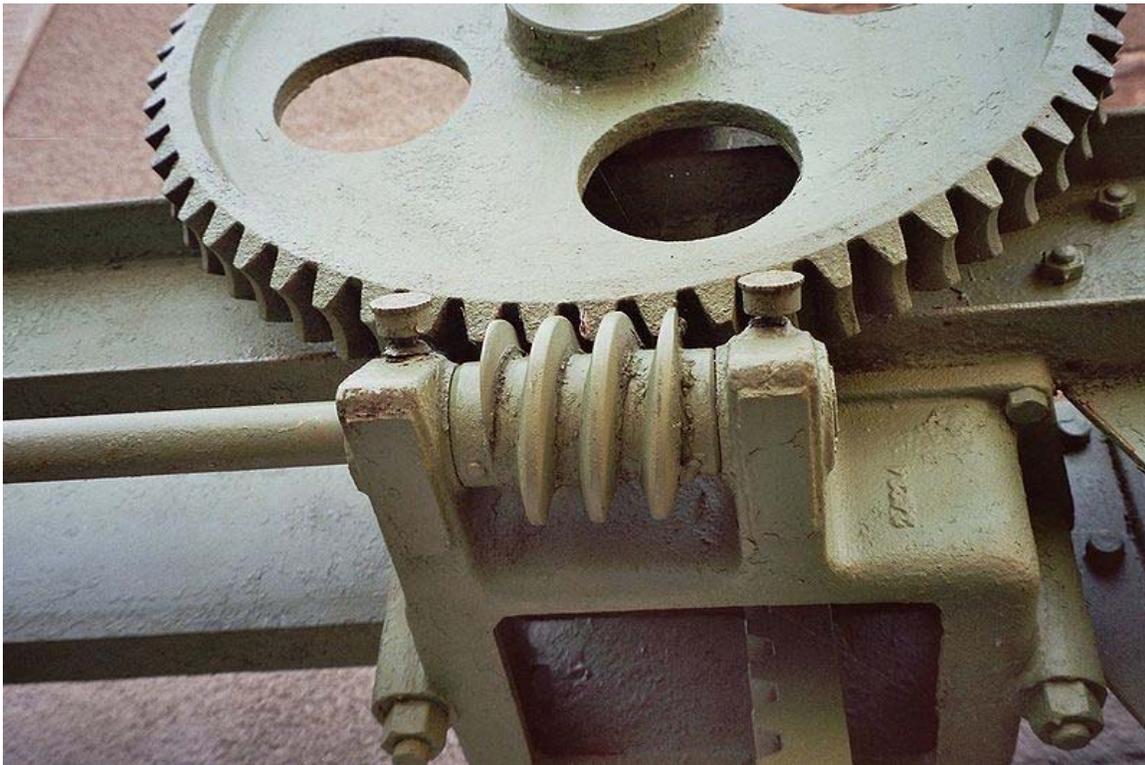
Double-enveloping wormgearing comprises enveloping worms mated with fully enveloping wormgears. It is also known as globoidal wormgearing.

Direction of transmission

Unlike with ordinary gear trains, the direction of transmission (input shaft vs output shaft) is not reversible when using large reduction ratios, due to the greater friction involved between the worm and worm-wheel, when usually a single start (one spiral) worm is used. This can be an advantage when it is desired to eliminate any possibility of the output driving the input. If a multistart worm (multiple spirals) then the ratio reduces accordingly and the *braking effect* of a worm and worm-gear may need to be discounted as the gear may be able to drive the worm.

Worm gear configurations in which the gear can not drive the worm are said to be *self-locking*. Whether a worm and gear will be self-locking depends on the lead angle, the pressure angle, and the coefficient of friction; however, it is approximately correct to say that a worm and gear will be self-locking if the tangent of the lead angle is less than the coefficient of friction.

Applications



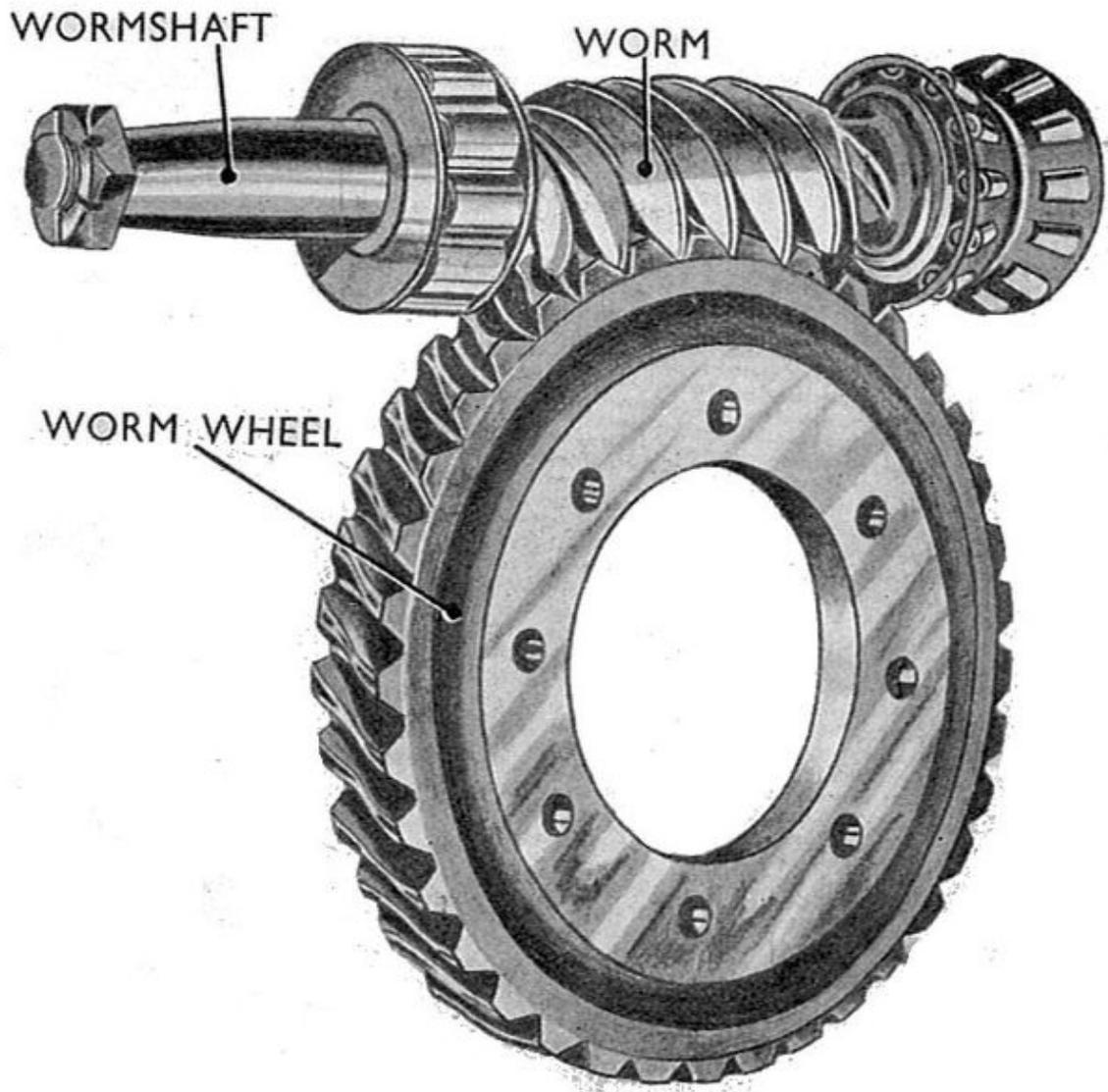
A worm drive controlling a gate. The position of the gate will not change after being set

In early 20th century automobiles prior to the introduction of power steering, the effect of a flat or blowout on one of the front wheels will tend to pull the steering mechanism toward the side with the flat tire. The employment of a worm screw reduced this effect. Further development of the worm drive employs recirculating ball bearings to reduce frictional forces, allowing some of the steering force to be felt in the wheel as an aid to vehicle control and greatly reducing wear, which leads to difficulties in steering precisely.

Worm drives are a compact means of substantially decreasing speed and increasing torque. Small electric motors are generally high-speed and low-torque; the addition of a worm drive increases the range of applications that it may be suitable for, especially when the worm drive's compactness is considered.

Worm drives are used in presses, in rolling mills, in conveying engineering, in mining industry machines, and on rudders. In addition, milling heads and rotary tables are positioned using high-precision duplex worm drives with adjustable backlash. Worm gears are used on many lift- (in US English known as elevator) and escalator-drive applications due to their compact size and the non-reversibility of the gear.

In the era of sailing ships, the introduction of a worm drive to control the rudder was a significant advance. Prior to its introduction, a rope drum drive was used to control the rudder, and rough seas could cause substantial force to be applied to the rudder, often requiring several men to steer the vessel, with some drives having two large-diameter wheels to allow up to four crewmen to operate the rudder.



Truck final drive of the 1930s

Worm drives have been used in a few automotive rear-axle final drives (although not the differential itself at this time). They took advantage of the location of the gear being at either the very top or very bottom of the differential crown wheel. In the 1910s they were common on trucks; to gain the most clearance on muddy roads the worm gear was placed on top. In the 1920s the Stutz firm used them on its cars; to have a lower floor than its competitors, the gear was located on the bottom. An example from around 1960 was the Peugeot 404. The worm gear carries the differential gearing, which protects the vehicle against rollback. This ability has largely fallen from favour due to the higher-than-necessary reduction ratios.

A more recent exception to this is the Torsen differential, which uses worms and planetary worm gears in place of the bevel gearing of conventional open differentials. Torsen differentials are most prominently featured in the HMMWV and some commercial Hummer vehicles, and as a center differential in some all wheel drive systems, such as Audi's quattro. Very heavy trucks, such as those used to carry aggregates, often use a worm gear differential for strength. The worm drive is not as efficient as a hypoid gear, and such trucks invariably have a very large differential housing, with a correspondingly large volume of gear oil, to absorb and dissipate the heat created.

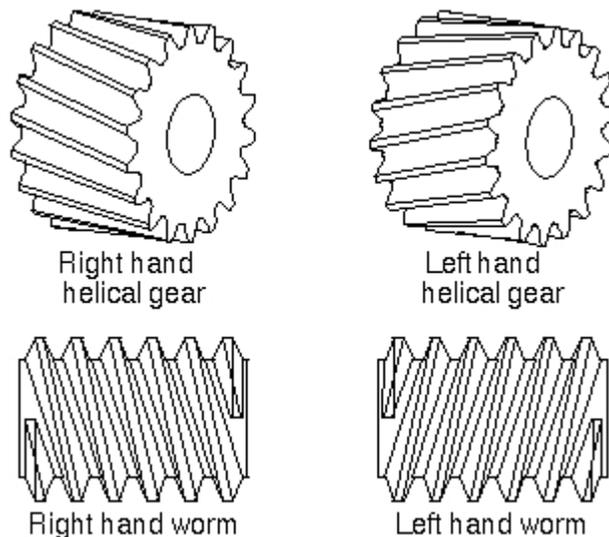
Worm drives are used as the tuning mechanism for many musical instruments, including guitars, double-basses, mandolins and bouzoukis, although not banjos, which use planetary gears or friction pegs. A worm drive tuning device is called a machine head.

Plastic worm drives are often used on small battery-operated electric motors, to provide an output with a lower angular velocity (fewer revolutions per minute) than that of the motor, which operates best at a fairly high speed. This motor-worm-gear drive system is often used in toys and other small electrical devices.

A worm drive is used on jubilee-type hose clamps or jubilee clamps; the tightening screw has a worm thread which engages with the slots on the clamp band.

Occasionally a worm gear is designed to be run in reverse, resulting in the output shaft turning much faster than the input. Examples of this may be seen in some hand-cranked centrifuges or the wind governor in a musical box.

Left hand and right hand worm



Helical and worm handedness

A right hand helical gear or right hand worm is one in which the teeth twist clockwise as they recede from an observer looking along the axis. The designations, right hand and left hand, are the same as in the long established practice for screw threads, both external and internal. Two external helical gears operating on parallel axes must be of opposite hand. An internal helical gear and its pinion must be of the same hand.

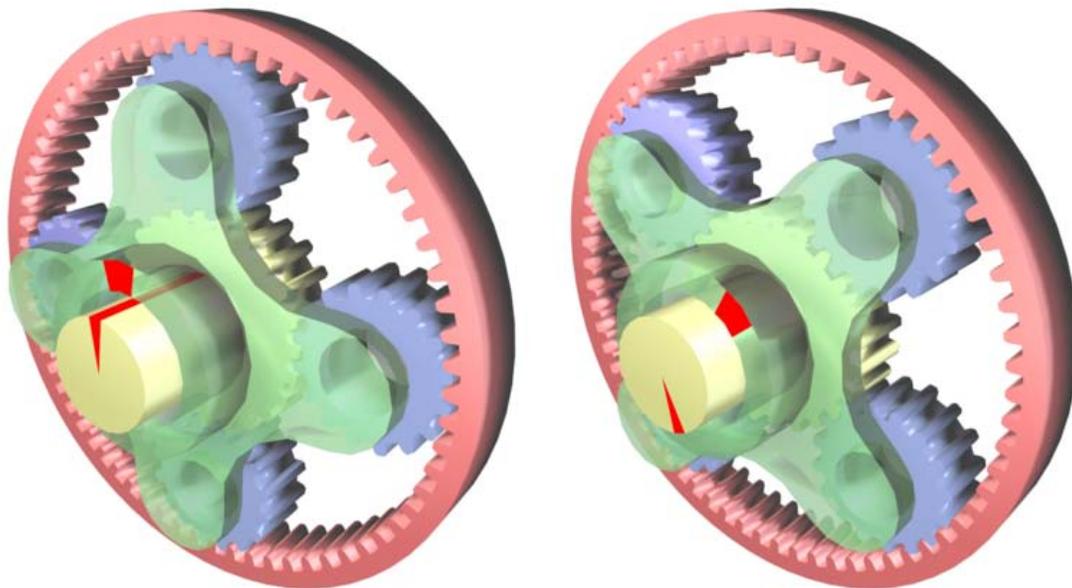
A left hand helical gear or left hand worm is one in which the teeth twist counterclockwise as they recede from an observer looking along the axis.

Manufacture

Worm wheels are first gashed to rough out the teeth and then hobbled to the final dimensions.

Chapter 5

Epicyclic Gearing

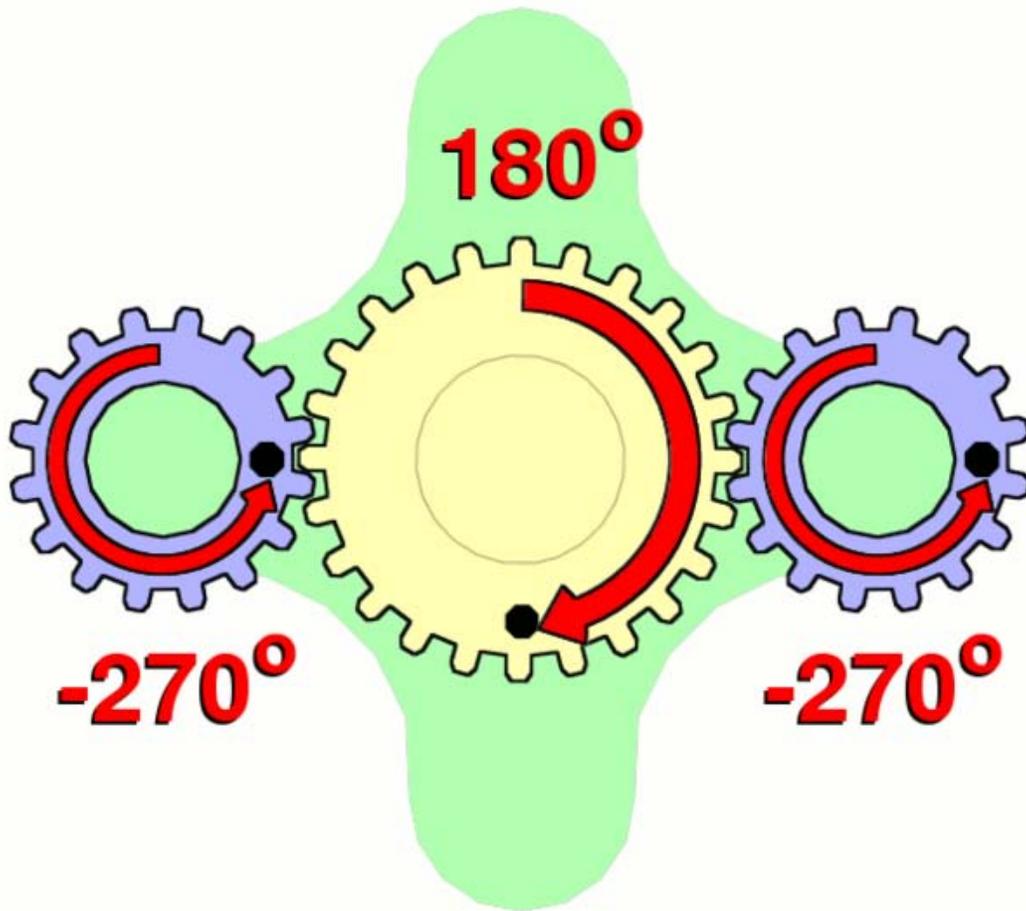


Epicyclic gearing is used here for increasing output speed. The planet gear carrier (green) is driven by an input torque. The sun gear (yellow) provides the output torque, while the ring gear (red) is fixed. Note the red marks both before and after the input drive is rotated 45° clockwise.

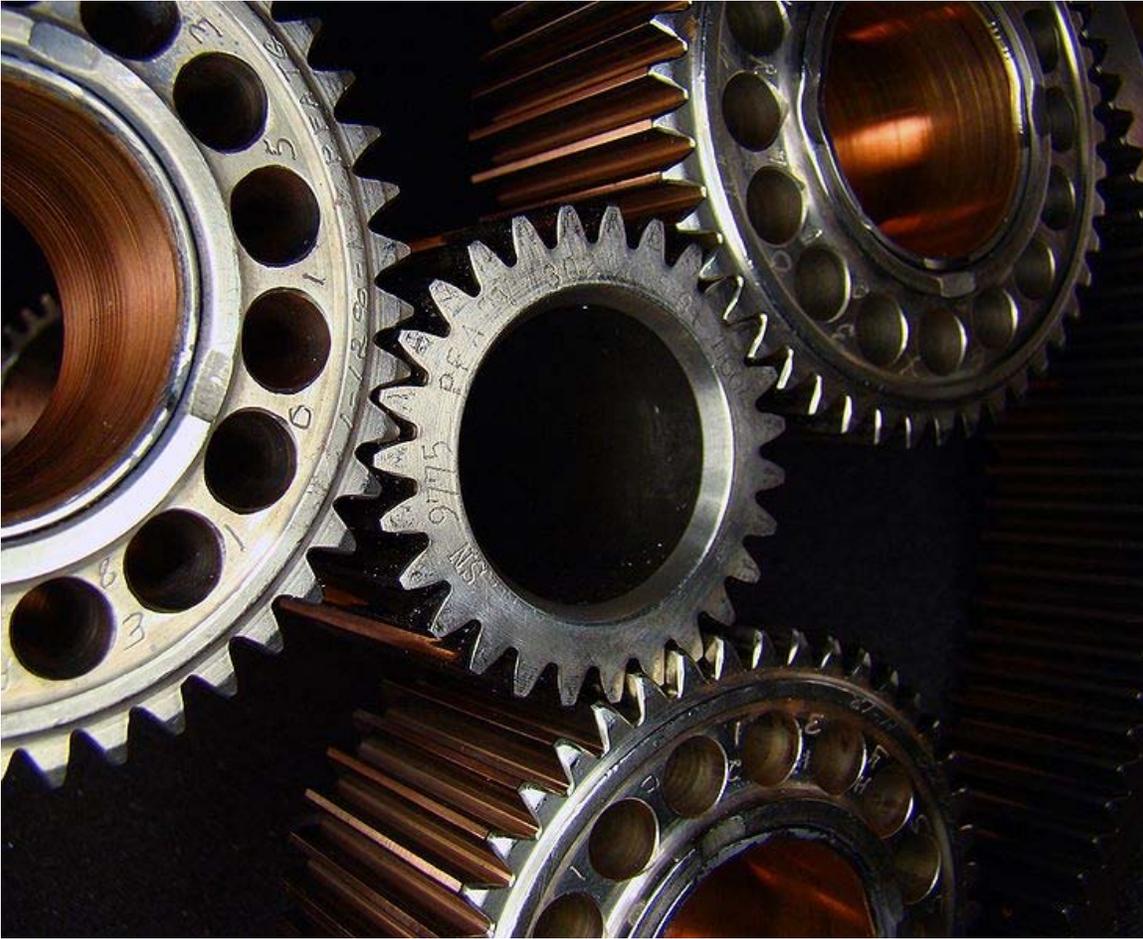
Epicyclic gearing or **planetary gearing** is a gear system consisting of one or more outer gears, or *planet* gears, revolving about a central, or *sun* gear. Typically, the planet gears are mounted on a movable arm or *carrier* which itself may rotate relative to the sun gear. Epicyclic gearing systems also incorporate the use of an outer ring gear or *annulus*, which meshes with the planet gears.

The axes of all gears are usually parallel, but for special cases like pencil sharpeners they can be placed at an angle, introducing elements of bevel gear (see below). Further, the sun, planet carrier and annulus axes are usually concentric.

Gear ratio



In this example, the carrier (green) is held stationary while the sun gear (yellow) is used as input. The planet gears (blue) turn in a ratio determined by the number of teeth in each gear. Here, the ratio is $-24/16$, or $-3/2$; each planet gear turns at $3/2$ the rate of the sun gear, in the opposite direction.



Reduction gears on Pratt & Whitney Canada PT6 gas turbine engine.

The gear ratio in an epicyclic gearing system is somewhat non-intuitive, particularly because there are several ways in which an input rotation can be converted into an output rotation. The three basic components of the epicyclic gear are:

- *Sun*: The central gear
- *Planet carrier*: Holds one or more peripheral *planet* gears, all of the same size, meshed with the sun gear
- *Annulus*: An outer ring with inward-facing teeth that mesh with the planet gear or gears

In many epicyclic gearing systems, one of these three basic components is held stationary; one of the two remaining components is an *input*, providing power to the system, while the last component is an *output*, receiving power from the system. The ratio of input rotation to output rotation is dependent upon the number of teeth in each gear, and upon which component is held stationary.

In other systems, such as hybrid vehicle transmissions, two of the components are used as *inputs* with the third providing *output* relative to the two inputs.

One situation is when the planetary carrier is held stationary, and the sun gear is used as input. In this case, the planetary gears simply rotate about their own axes at a rate determined by the number of teeth in each gear. If the sun gear has N_s teeth, and each planet gear has N_p teeth, then the ratio is equal to $-N_s/N_p$. For instance, if the sun gear has 24 teeth, and each planet has 16 teeth, then the ratio is $-24/16$, or $-3/2$; this means that one clockwise turn of the sun gear produces 1.5 *counterclockwise* turns of each of the planet gear(s) about its axis.

This rotation of the planet gears can in turn drive the annulus, in a corresponding ratio. If the annulus has N_a teeth, then the annulus will rotate by N_p/N_a turns for each turn of the planet gears. For instance, if the annulus has 64 teeth, and the planets 16, one clockwise turn of a planet gear results in $16/64$, or $1/4$ clockwise turns of the annulus. Extending this case from the one above:

- One turn of the sun gear results in $-N_s / N_p$ turns of the planets
- One turn of a planet gear results in N_p / N_a turns of the annulus

So, with the planetary carrier locked, one turn of the sun gear results in $-N_s / N_a$ turns of the annulus.

The annulus may also be held fixed, with input provided to the planetary gear carrier; output rotation is then produced from the sun gear. This configuration will produce an increase in gear ratio, equal to $1+N_a/N_s$.

These are all described by the equation:

$$(2 + n)\omega_a + n\omega_s - 2(1 + n)\omega_c = 0$$

where n is the form factor of the planetary gear, defined by:

$$n = N_s / N_p$$

If the annulus is held stationary and the sun gear is used as the input, the planet carrier will be the output. The gear ratio in this case will be $1/(1+N_a/N_s)$. This is the lowest gear ratio attainable with an epicyclic gear train. This type of gearing is sometimes used in tractors and construction equipment to provide high torque to the drive wheels.

In bicycle hub gears, the sun is usually stationary, being keyed to the axle or even machined directly onto it. The planetary gear carrier is used as input. In this case the gear ratio is simply given by $(N_s+N_a)/N_a$. The number of teeth in the planet gear is irrelevant.

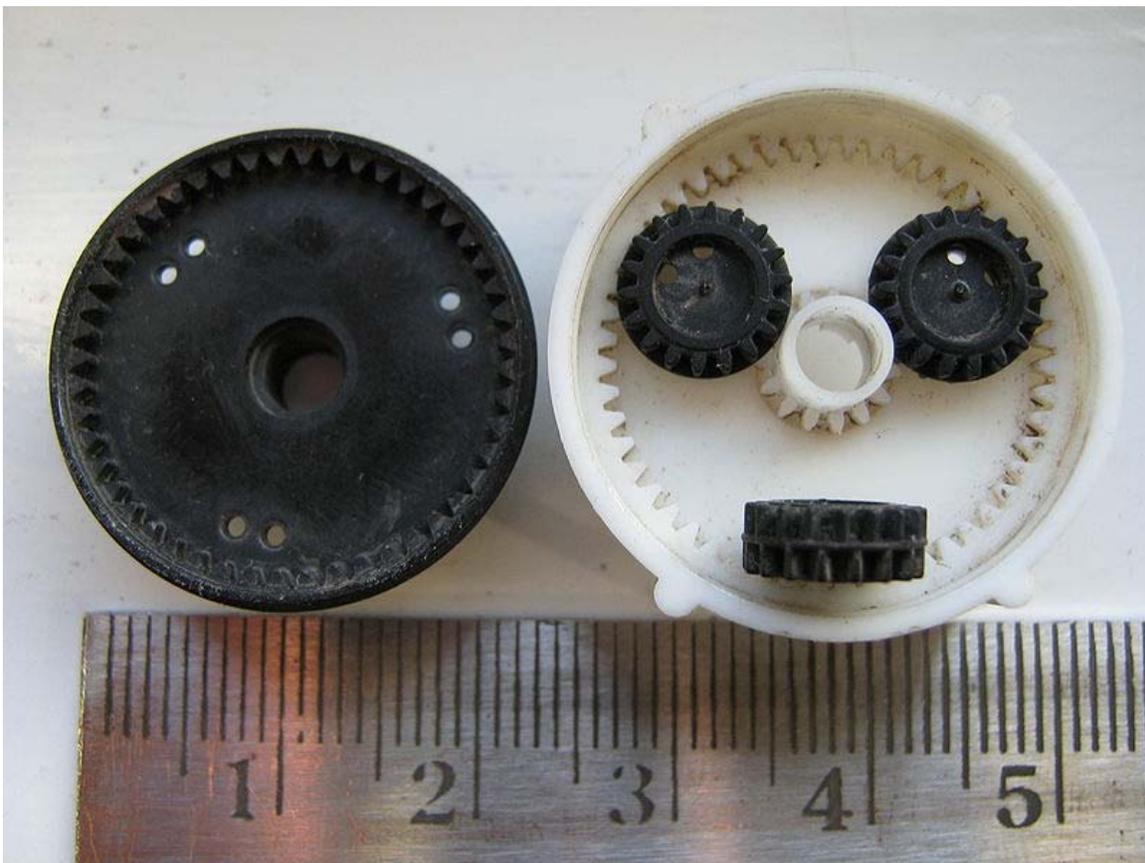


Compound planets of a Sturmey-Archer AM bicycle hub (gear ring removed)

Some designs use "compound planets" which have two differently-sized gears on either end of a common casting. The large end engages the sun, while the small end engages the annulus. This may be necessary to achieve smaller step changes in gear ratio when the overall package size is limited. Compound planets have "timing marks" and must be assembled in the correct initial orientation relative to each other, or their teeth will not simultaneously engage the sun and annulus at opposite ends of the planet, leading to very rough running and short life. The use of compound planets is like increasing the size of the annulus; for example, compound planets with teeth in a 2:1 ratio with a 50T annulus would give the same effect as a 100T annulus, but with half the actual diameter.

More planet and sun gear units can be placed in series in the same annulus housing (where the output shaft of the first stage becomes the input shaft of the next stage) providing a larger (or smaller) gear ratio. This is the way some automatic transmissions work.

During World War II, a special variation of epicyclic gearing was developed for portable radar gear, where a very high reduction ratio in a small package was needed. This had two outer annular gears, each half the thickness of the other gears. One of these two annular gears was held fixed and had one tooth fewer than did the other. Therefore, several turns of the "sun" gear made the "planet" gears complete a single revolution, which in turn made the rotating annular gear rotate by a single tooth.



Split annulus, compound planet, epicyclic gears of a car rear-view mirror positioner



The mechanism of a pencil sharpener with stationary annulus and rotating planet carrier as input. Planet gears are extended into cylindric cutters, rotating around the pencil that is placed on the sun axis. The axis of planetary gears join at pencil sharpening angle.



Calculating the output from the input

It is first drawn simplified as the sun, a single planet, the annulus, and an arm holding the planet. Any gear can be the input or output, including the arm.

Now, put in the known values and solve for ω_{ring} :

$$\frac{N_{sun}}{N_{ring}} = \frac{\omega_{arm} - \omega_{ring}}{\omega_{sun} - \omega_{arm}}$$

or you can use the other form of this equation:

$$N_{sun} \cdot \omega_{sun} + N_{ring} \cdot \omega_{ring} = (N_{ring} + N_{sun}) \cdot \omega_{arm}$$

where N is the number of teeth, ω is angular velocity of the element (sun, arm, or ring). Since the angular velocity and rpm are directly proportional, you can use rpm instead.

However, if the arm is the input or output, say the ring is the output/input instead and reverse the direction (since if the arm moves a certain speed relative to the ring, the ring moves that same speed the other way relative to the arm, and obviously the arm does not have a tooth count to plug in)

To derive this, just imagine the arm is locked, and calculate the gear ratio $\omega_{ring} / \omega_{sun} = N_{sun} / N_{ring}$, then unlock the arm. From the arms reference frame the ratio is always N_{sun}/N_{ring} , but from your frame all the speeds are increased by the angular velocity of the arm. So to write this relative relationship, you arrive at the equation from above.

Also, make sure $N_{sun} + 2N_{planet} = N_{ring}$ where N is the number of teeth. This simply says that the gears will fit, since N is directly proportional to diameter.

Advantages and disadvantages

Advantages of planetary gears over parallel axis gears include high power density, large reduction in a small volume, multiple kinematic combinations, pure torsional reactions, and coaxial shafting. Disadvantages include high bearing loads, inaccessibility, and design complexity. The planetary gearbox arrangement is an engineering design that offers many advantages over traditional gearbox arrangements. One advantage is its unique combination of both compactness and outstanding power transmission efficiencies. A typical efficiency loss in a planetary gearbox arrangement is only 3% per stage. This type of efficiency ensures that a high proportion of the energy being input is transmitted through the gearbox, rather than being wasted on mechanical losses inside the gearbox.

Another advantage of the planetary gearbox arrangement is load distribution. Because the load being transmitted is shared between multiple planets, torque capability is greatly

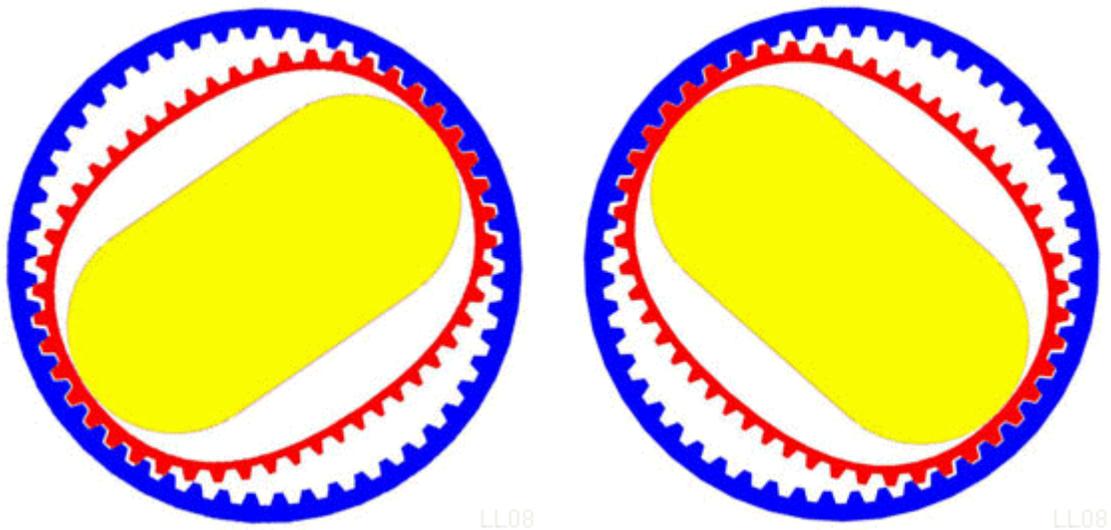
increased. The more planets in the system, the greater load ability and the higher the torque density.

The planetary gearbox arrangement also creates greater stability due to the even distribution of mass and increased rotational stiffness.

Chapter 6

Harmonic Drive and Non-Circular Gear

Harmonic drive



Harmonic drive

A **Harmonic Drive** (also known as "Strain Wave Gearing") is a special type of mechanical gear system that can improve certain characteristics compared to traditional gearing systems (such as Helical Gears or Planetary Gears). It was invented in 1957 and is now produced by Harmonic Drive LLC. The advantages include: no backlash, compactness and light weight, high gear ratios, reconfigurable ratios within a standard housing, good resolution and repeatability when repositioning inertial loads, high torque capability, and coaxial input and output shafts. High gear reduction ratios are possible in a small volume (a ratio of 100:1 is possible in the same space in which planetary gears typically only produce a 10:1 ratio).

Disadvantages include a tendency for 'wind-up' (a torsional spring rate) and potential degradation over time from mechanical shocks and environment.

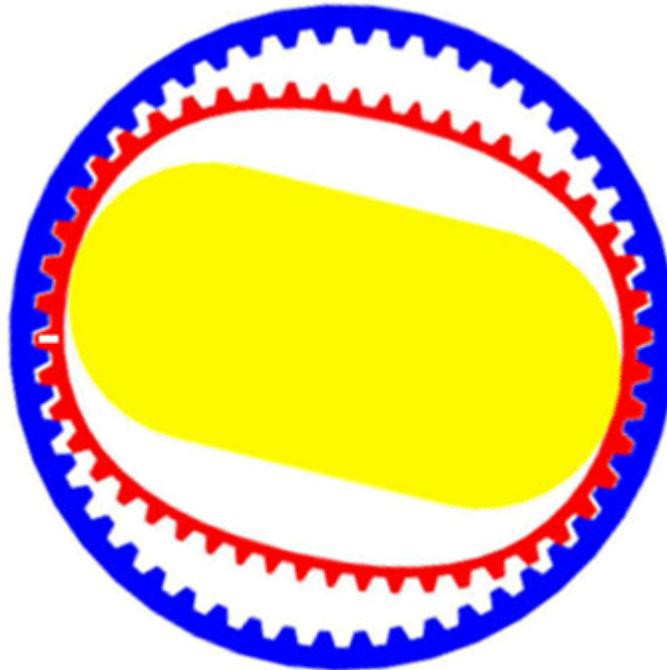
They are typically used in industrial motion control, robotics and aerospace, for gear reduction but may also be used to increase rotational speed, or for differential gearing.

History

The basic concept of Strain Wave Gearing (SWG) was introduced by C.W. Musser in his 1957 patent. It was first used successfully in 1964 by Hasegawa Gear Works, Ltd. and USM Co., Ltd. Later, Hasegawa Gear Works, Ltd. became Harmonic Drive Systems Inc. located in Japan and USM Co., Ltd. Harmonic Drive division became Harmonic Drive Technologies Inc.

On January 1, 2006, Harmonic Drive Technologies/Nabtesco of Peabody, MA and HD Systems of Hauppauge, NY, merged to form a new joint venture, Harmonic Drive LLC. HD Systems, Inc. was a subsidiary company of Harmonic Drive System, Inc. Offices are maintained in both Peabody and Hauppauge.

Mechanics



Cross-section of a Strain Wave Gearing.

A: circular spline (fixed)

B: flex spline (attached to output shaft, not shown)

C: wave generator (attached to input shaft, not shown)

The Strain Wave Gearing theory is based on elastic dynamics and utilizes the flexibility of metal. The mechanism has three basic components: a wave generator, a flex spline, and a circular spline. More complex versions have a fourth component normally used to

shorten the overall length or to increase the gear reduction within a smaller diameter, but still follow the same basic principles.

The wave generator is made up of two separate parts: an elliptical disk called a *wave generator plug* and an outer ball bearing. The gear plug is inserted into the bearing, giving the bearing an elliptical shape as well.

The flex spline is like a shallow cup. The sides of the spline are very thin, but the bottom is thick and rigid. This results in significant flexibility of the walls at the open end due to the thin wall, but in the closed side being quite rigid and able to be tightly secured (to a shaft, for example). Teeth are positioned radially around the outside of the flex spline. The flex spline fits tightly over the wave generator, so that when the wave generator plug is rotated, the flex spline deforms to the shape of a rotating ellipse but does not rotate with the wave generator.

The circular spline is a rigid circular ring with teeth on the inside. The flex spline and wave generator are placed inside the circular spline, meshing the teeth of the flex spline and the circular spline. Because the flex spline has an elliptical shape, its teeth only actually mesh with the teeth of the circular spline in two regions on opposite sides of the flex spline, along the major axis of the ellipse.

Assume that the wave generator is the input rotation. As the wave generator plug rotates, the flex spline teeth which are meshed with those of the circular spline change. The major axis of the flex spline actually rotates with wave generator, so the points where the teeth mesh revolve around the center point at the same rate as the wave generator. The key to the design of the harmonic drive is that there are fewer teeth (for example two fewer) on the flex spline than there are on the circular spline. This means that for every full rotation of the wave generator, the flex spline would be required to rotate a slight amount (two teeth, for example) backward relative to the circular spline. Thus the rotation action of the wave generator results in a much slower rotation of the flex spline *in the opposite direction*.

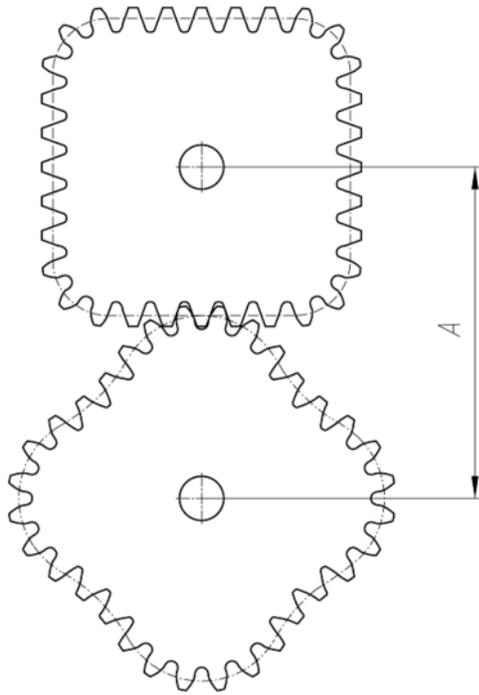
For a Strain Wave Gearing mechanism, the gearing reduction ratio can be calculated from the number of teeth on each gear:

$$\text{reduction ratio} = \frac{\text{flex spline teeth} - \text{circular spline teeth}}{\text{flex spline teeth}}$$

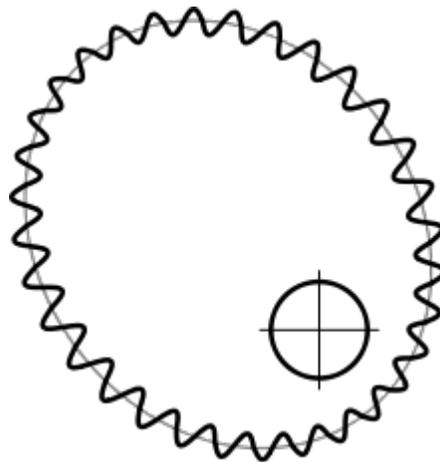
For example, if there are 202 teeth on the circular spline and 200 on the flex spline, the reduction ratio is $(200 - 202)/200 = -0.01$

Thus the flex spline spins at 1/100 the speed of the wave generator plug and in the opposite direction. This allows different reduction ratios to be set without changing the mechanism's shape, increasing its weight, or adding stages. The range of possible gear ratios is limited by teeth size limits for a given configuration.

Non-Circular gear



Non-circular gear example



Another non-circular gear

A **non-circular gear (NCG)** is a special gear design with special characteristics and purpose. While a regular gear is optimized to transmit torque to another engaged member with minimum noise and wear and with maximum efficiency, a non-circular gear's main objective might be ratio variations, axle displacement oscillations and more. Common

applications include textile machines, potentiometers and CVTs (continuously variable transmissions). Many bicycles have an elliptical gear, see, eg., Biopace.

A regular gear pair can be represented as two circles rolling together without slip. In the case of non-circular gears, those circles are replaced with anything different from a circle. This is also the reason NCG in most cases is not round, however round NCGs looking like regular gears are possible too (small ratio variations result from meshing area modifications).

Generally NCG should meet all the requirements of regular gearing, but in some cases, for example variable axle distance, could prove impossible to support and such gears require very tight manufacturing tolerances and assembling problems arise. Because of complicated geometry, NCGs are most likely spur gears and molding or electrical discharge machining technology is used instead of generation.

Mathematical description

Ignoring the gear teeth for the moment (i.e. assuming the gear teeth are very small), let $r_1(\theta_1)$ be the radius of the first gear wheel as a function of angle from the axis of rotation θ_1 , and let $r_2(\theta_2)$ be the radius of the second gear wheel as a function of angle from its axis of rotation θ_2 . If the axles remain fixed, the distance between the axles is also fixed:

$$r_1(\theta_1) + r_2(\theta_2) = a$$

Assuming that the point of contact lies on the line connecting the axles, in order for the gears to touch without slipping, the velocity of each wheel must be equal at the point of contact and perpendicular to the line connecting the axles, which implies that:

$$r_1 d\theta_1 = r_2 d\theta_2$$

Of course, each wheel must be cyclic in its angular coordinates. If the shape of the first wheel is known, the shape of the second can often be found using the above equations. If the relationship between the angles is specified, the shapes of both wheels can often be determined analytically as well.

It is more convenient to use the circular variable $z = e^{i\theta}$ when analyzing this problem. Assuming the radius of the first gear wheel is known as a function of z , and using the relationship $dz = iz d\theta$, the above two equations can be combined to yield the differential equation:

$$\frac{dz_2}{z_2} = \frac{r_1(z_1)}{a - r_1(z_1)} \frac{dz_1}{z_1}$$

where z_1 and z_2 describe the rotation of the first and second gears respectively. This equation can be formally solved as:

$$\ln(z_2) = \ln(K) + \int \frac{r_1(z_1)}{a - r_1(z_1)} \frac{dz_1}{z_1}$$

where $\ln(K)$ is a constant of integration.

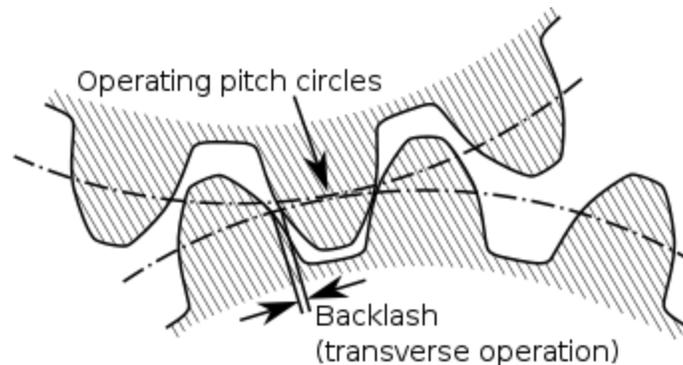
Chapter 7

Backlash (Engineering)

In mechanical engineering, **backlash**, sometimes called **lash** or **play**, is clearance between mating components, sometimes described as the amount of lost motion due to clearance or slackness when movement is reversed and contact is re-established. For example, in a pair of gears, backlash is the amount of clearance between mated gear teeth.

Theoretically, the backlash should be zero, but in actual practice some backlash must be allowed to prevent jamming. It is unavoidable for nearly all reversing mechanical couplings, although its effects can be negated. Depending on the application it may or may not be desirable. Reasons for requiring backlash include allowing for lubrication, manufacturing errors, deflection under load and thermal expansion.

Gears



Backlash

Factors affecting the amount backlash required in a gear train include errors in profile, pitch, tooth thickness, helix angle and center distance, and runout. The greater the accuracy the smaller the backlash needed. Backlash is most commonly created by cutting the teeth deeper into the gears than the ideal depth. Another way of introducing backlash is by increasing the center distances between the gears.

Backlash due to tooth thickness changes is typically measured along the pitch circle and is defined by:

$$b_t = t_i - t_a$$

where:

b_t = backlash due to tooth thickness modifications

t_i = tooth thickness on the pitch circle for ideal gearing (no backlash)

t_a = actual tooth thickness

Backlash, measured on the pitch circle, due to operating center modifications is defined by:

$$b_c = 2(\Delta c) \tan \phi$$

where:

b_c = backlash due to operating center distance modifications

Δc = difference between actual and ideal operating center distances

ϕ = pressure angle

Standard practice is to make allowance for half the backlash in the tooth thickness of each gear. However, if the pinion (the smaller of the two gears) is significantly smaller than the gear it is meshing with then it is common practice to account for all of the backlash in the larger gear. This maintains as much strength as possible in the pinion's teeth. The amount of additional material removed when making the gears depends on the pressure angle of the teeth. For a 14.5° pressure angle the extra distance the cutting tool is moved in equals the amount of backlash desired. For a 20° pressure angle the distance equals 0.73 times the amount of backlash desired.

As a rule of thumb the average backlash is defined as 0.04 divided by the diametral pitch; the minimum being 0.03 and the maximum 0.05.

In a gear train, backlash is cumulative. When a gear-train is reversed the driving gear is turned a short distance, equal to the total of all the backlashes, before the final driven gear begins to rotate. At low power outputs, backlash results in inaccurate calculation from the small errors introduced at each change of direction; at large power outputs backlash sends shocks through the whole system and can damage teeth and other components.

Anti-backlash designs

In certain applications, backlash is an undesirable characteristic and should be minimized; for example, a radio tuning dial where one may make precise tuning

movements both forwards and backwards. Specialised gear designs allow this. One of the more common designs splits the gear into two gears, each half the thickness of the original. One half of the gear is fixed to its shaft while the other half of the gear is allowed to turn on the shaft, but pre-loaded in rotation by small coil springs that rotate the free gear relative to the fixed gear. In this way, the spring tension rotates the free gear until all of the backlash in the system has been taken out; the teeth of the fixed gear press against one side of the teeth of the pinion while the teeth of the free gear press against the other side of the teeth on the pinion. Loads smaller than the force of the springs do not compress the springs and with no gaps between the teeth to be taken up, backlash is eliminated.

High-precision main drives and positioning drives of CNC machine tools use duplex worm gear sets for backlash adjustment.

In mechanical computers a more complex solution is required, namely a frontlash gearbox. This works by turning slightly faster when the direction is reversed to 'use up' the backlash slack.

Some motion controllers include backlash compensation. Compensation may be achieved by simply adding extra compensating motion or by sensing the load's position in a closed loop control scheme. The dynamic response of backlash itself, essentially a delay, makes the position loop less stable and prone to oscillation.

Minimum backlash

Minimum backlash is the minimum transverse backlash at the operating pitch circle allowable when the gear tooth with the greatest allowable functional tooth thickness is in mesh with the pinion tooth having its greatest allowable functional tooth thickness, at the tightest allowable center distance, under static conditions.

Difference between the maximum and minimum backlash occurring in a whole revolution of the larger of a pair of mating gears.

Applications

Gear couplings use backlash to allow for angular misalignment.

Backlash is undesirable in precision positioning applications such as machine tool tables. It can be minimized by tighter design features such as ball screws instead of leadscrews, and by using preloaded bearings. A preloaded bearing uses a spring or other compressive force to maintain bearing surfaces in contact despite reversal of direction.

There can be significant backlash in unsynchronized transmissions because of the intentional gap between dog gears (also known as dog clutches). The gap is necessary so that the driver or electronics can engage the gears easily while synchronizing the engine speed with the driveshaft speed. If there was a small clearance, it would be nearly

impossible to engage the gears because the teeth would interfere with each other in most configurations. In synchronized transmissions, synchromesh solves this problem.

Chapter 8

Bicycle Gearing



A bicycle with a hub gear.



Shimano XT rear derailleur on a mountain bike

A bicycle **gear**, or **gear ratio**, or **speed** refers to the rate at which the rider's legs turn compared to the rate at which the wheels turn. **Bicycle gearing** refers to how the gear ratio is set or changed. On some bicycles, there is only one gear so the ratio is fixed. Most modern bicycles have multiple gears, so multiple gear ratios are possible. Different gears and ranges of gears are appropriate for different people and styles of cycling.

Multi-speed bicycles allow selection of the appropriate gear ratio for optimum efficiency or comfort, and to suit the circumstances, e.g. it may be comfortable to use one gear when cycling downhill, another when cycling on a flat road, and yet another when cycling uphill. The set of all possible gear ratios on a bicycle is known as the 'gear range'.

A cyclist's legs produce power optimally within a narrow pedalling speed range. Gearing is optimized to use this narrow range as best as possible. As in other types of transmissions, the gear ratio is closely related to the mechanical advantage of the drivetrain of the bicycle. On single-speed bicycles and multi-speed bicycles using derailleur gears, the gear ratio is the ratio of the number of teeth on the chainring of the crankset to the rear cog or sprocket, or the ratio of bevel gears on a shaft-driven bicycle. In the case of a derailleur-equipped bicycle, this sprocket is one of several composing the cogset. On hub gears, the ratio is determined by the internal planetary gears within the hub, in addition to the chainwheel/sprocket ratio.

For a bicycle to travel at the same speed, set to a lower gear (larger mechanical advantage) it will require the rider to pedal at a faster cadence, but with less force. Conversely, a higher gear (smaller mechanical advantage) provides a higher speed for a given cadence, but requires the driver to exert greater force. Different cyclists may have different preferences for cadence and pedaling force. Prolonged exertion of too much force in too high a gear at too low a cadence can increase the chance of knee damage; extremely high cadence and little force maintained at too low a gear also is not advised.

General considerations

The gearing supplied by the manufacturer on a new bicycle is selected to be useful to the majority of people. Some cyclists choose to fine-tune the gearing to better suit their strength, level of fitness, and expected usage. When buying from specialist cycle shops, it may be less expensive to get the gears altered before delivery rather than at some later date. Modern crankset chainrings can be swapped out, as can cogsets.

Relative gearing

As far as a cyclist's legs are concerned, when changing gears, the relative difference between two gears is more important than the absolute difference between gears. This relative change, from a lower gear to a higher gear, is normally expressed as a percentage. This measure is independent of what system is used to measure the gears. Cycling tends to feel more comfortable if nearly all gear changes have more or less the same percentage difference; a larger percentage difference may be acceptable for lower gears where the absolute difference is not too large. Thus, the absolute gear ratios should be in logarithmic progression; for example 24-35-51 / 34-28-23-19-16-13-11 has a nearly logarithmic progression in steps the same size as the oldest 3-speed planetary hubs, many duplicates, and a very wide range. Modern derailleurs can handle such combinations.

Racing cyclists often have close-range gears with a difference of around 7%. Many general-purpose gears have a difference of around 15%. Differences of 25% or more require a very substantial change in cadence and often feel excessive. A step of 7% corresponds to a 1-tooth change from a 14-tooth sprocket to a 15-tooth sprocket, while a step of 15% corresponds to a 2-tooth change from a 13-tooth sprocket to a 15-tooth sprocket.

By contrast, car engines deliver power over a much larger range of speeds than cyclists' legs do, so relative differences of 30% or more are common for car gearboxes.

Usable gears

The number of gears for a derailleur equipped bike is often stated simplistically, particularly in advertising, which may be misleading. A combination of 3 chainrings and an 8-cog cassette does not result in 24 usable gears. Instead it provides 3 overlapping ranges of 7, 8, and 7 gears. Due to the overlap, there may well be some duplicates or near-duplicates, so that there might only be 16 or 18 distinct gears. It may not be feasible to use these distinct gears in strict low-high sequence anyway due to the complicated shifting patterns involved (e.g. simultaneous double or triple shift on the rear derailleur and a single shift on the front derailleur). Also, the extremes of largest chain-ring to largest rear sprocket ("rear cog") and smallest chainring to smallest rear sprocket should not be used because these combinations cause the chain to align to the gears off-angle which reduces efficiency and causes excessive chain wear. In the worst case there could be only 10 distinct gears, if the percentage step between chainrings is the same as the step between sprockets. However, in such a worst case, if the most popular gear is in the middle of the range, the duplication may result in a gear set with a very long useful life, which may be an advantage.

One archaic tactic for avoiding this duplication is to use chainrings of similar size. On a modern bicycle, it might be possible to move from one speed to its duplicate by shifting to the next smaller chainring and the third smaller sprocket. This would be because the chainrings have large gaps in their size: In this example, the ratio of the chainrings is approximately three times the ratio of the sprockets. This would be called a **crossover** gearing configuration, specifically a "three-step crossover." A bicycle with two chainrings that were close to each other in size would theoretically avoid duplication. The ratio of the chainrings would need to be approximately half that of the sprockets. In this configuration, the **half-step** configuration, the speeds on one chainring would be between those on the other chainring, eliminating duplication. This configuration was complicated to design, since the "step" is actually an exponent, not a multiple. That is, (sprocket ratio)³ for a three step or (sprocket ratio)^(1/2) for a half step. Since limited sprocket options prevented a constant ratio between the sprockets, there would still be duplication in practice. Getting a low gear combination would require a third, much smaller chainring; a configuration derogatorily called a **half-step-plus-granny**. The frequent front-shifting and combined front-and-rear shifting made these configurations generally impractical.

While long steep hills and heavy loads may indicate lower gearing, extremely low gears may not allow the rider to maintain the minimum speed necessary to balance a single-track vehicle.

Implementation

The overlapping ranges with derailleur gears mean that 24 or 27 speed derailleur gears may only have the same total gear range (about 5:1) as a (much more expensive) Rohloff

14-speed hub gear. Internal hub geared bikes typically have a more restricted gear range than comparable derailleur-equipped bikes, and have fewer ratios within that range.

Types

External (derailleur)

External gearing utilizes derailleurs, which can be placed on both the front chainring and on the rear cogset, to push the chain to either side, derailing it from one sprocket to a neighboring sprocket. The sides of the sprockets may be sculpted to help catch the chain, pulling it up onto their teeth to change gears. There may be 1 to 3 chainrings, and 5 to 11 sprockets on the cogset. Derailleur type mechanisms of a typical mid-range product (of the sort used by serious amateurs) achieve between 88% and 99% mechanical efficiency at 100W. In derailleur mechanisms the highest efficiency is achieved by the larger sprockets. Efficiency generally decreases with smaller sprocket and chainring sizes. Derailleur efficiency is also compromised with *cross-chaining*, or running large-ring to large-sprocket or small-ring to small-sprocket. This cross-chaining also results in increased wear because of the lateral deflection of the chain.

Internal (hub)

Internal hub gears work by internal planetary, or epicyclic, gearing, in which the hub outer turns at a different, but adjustable, speed relative to the sprocket. Rear hub gears commonly come in 3 or 7 speeds but with many variations and up to 14 speeds. Internal hub gears are more reliable than derailleurs, clean, almost weather-proof and require little maintenance. Only the most expensive offer as wide a range of gear ratios as derailleurs.

In a typical hub gear mechanism the mechanical efficiency will be between 82% and 92% depending on the ratio selected. One to one ratios are generally the most efficient, while systems employing several epicyclic trains in series (compound gears) are the least efficient.

Internal hub gearing predominate in bicycles used for city-riding and commuting, not least for the great convenience of changing down ratios while stationary. External derailleur systems predominate in competition and leisure use.

Internal (bottom bracket)

These systems have a 2-speed hub gear incorporated in the chain set.

The Schlumpf Mountain Drive and Speed Drive have been available since 2001 and offer direct drive plus one of three variants (reduction 1:2.5, increase 1.65:1, and increase 2.5:1). Changing gears is accomplished by using your foot to tap a button protruding on each side of the bottom bracket spindle. The effect is that of having a bicycle with twin chain rings with a massive difference in sizes.

Another system entered the market in 2010.

Fixed gear

Fixed-gear track racing bikes can achieve transmission efficiencies of over 99% (nearly all the energy put in at the pedals ends up at the wheel). Biomechanical factors however determine that a human can deliver maximum power only over a narrow range of crank rotational speed or *cadence*. To match the power source with the load under varying conditions, a variable gear ratio is needed, and they work very well, though at the expense of mechanical efficiency. The efficiency varies considerably with the gear ratio being used.

Internal and external combined

It is sometimes possible to combine a hub gear with derailleur gears, but care is needed when selecting the rear cassette to avoid duplicate gear ratios. There are several commercially available possibilities:

- The Brompton folding bicycle uses a 3-speed hub gear (roughly a 30% difference between gears) in combination with a 2-speed derailleur gear (roughly a 15% difference) to give 6 distinct gears. This is an example of half-step gearing, where one set of gears has an inter-gear step half of that on the other set of gears. Some Brompton suppliers offer a 2-speed chain ring 'Mountain Drive' as well, which results in 12 distinct gears with a range exceeding 5:1. However, the change from 6th to 7th gear involves changing all three sets of gears simultaneously. Many hub gears are capable of accepting two dished sprockets, allowing this system to be easily replicated.
- The SRAM DualDrive system uses a standard 8 or 9-speed cassette mounted on a three-speed internally-g geared hub, offering a similar gear range to a bicycle with a cassette and triple chainwheels.
- Less common is the use of a double or triple chainring in conjunction with an internally-g geared hub, extending the gear range without having to fit multiple sprockets to the hub. However, this does require a chain tensioner or some sort, negating some of the advantages of hub gears.
- At an extreme opposite from a single speed bicycle, hub gears can be combined with both front and rear derailleurs, giving a very wide-ranging drivetrain at the expense of weight and complexity of operation- there are a total of three sets of gears (four if a 2-speed bottom bracket is also used.) This approach may be suitable for recumbent trikes, where very low gears can be used without balance issues, and the aerodynamic position allows higher gears than normal.

Others

There have been, and still are, drivetrains that are quite different from those above:

- Retro-Direct drivetrains used on some early 20th century bicycles have been resurrected by bicycle hobbyists. These have two gears but no gear lever; the operator simply pedals forward for one gear and backward for the other.

- Automatic transmissions have been demonstrated and marketed for both derailleur and hub gear mechanisms, often accompanied by a warning to disengage auto-shifting if standing on the pedals. These have met with limited market success.
- Continuously variable transmissions are a relatively new development in bicycles (though not a new idea). Mechanisms like the NuVinci gearing system use a ball connected to two disks by static friction - changing the point of contact changes the gear ratio.

Efficiency of the two common gearing systems

Chester Kyle and Frank Berto reported in "Human Power" 52 (Summer 2001) that testing on three derailleur systems (from 4 to 27 gears) and eight gear hub transmissions (from 3 to 14 gears), performed with 80W, 150W, 200W inputs, gave results as follows:

Transmission Type Efficiency (%)

Derailleurs	87-97
Gear Hubs	86-95

Efficiency testing of bicycle gearing systems is complicated by a number of factors - in particular, all systems tend to be better at higher power rates. 200 Watts will drive a typical bicycle at 20 mph, while top cyclists can achieve 400W, at which point one hub-gear manufacturer (Rohloff) claims 98% efficiency.

At a more typical 150W, hub-gears tend to be around 2% less efficient than a well-lubricated derailleur.

Measuring gears

With a derailleur-based multi-speed bicycle, the gears can be denoted by the number of teeth on the front chainring and rear sprocket, for example the highest gear on a racing bicycle might be 53x11. For a road-racing cyclist, this is useful because of the standard size of the wheel. However, this measure is limited because it does not specify other aspects of the system. *Gear inches* and *metres of development* are related measures that include the diameter of the rear wheel. *Gain ratio* is a measure which also takes the length of the crankarms into account.

With a hub gear, gear ratios are given directly.

Gear inches and meters of development of a gear combination are defined:

- Gear inches = **Diameter** of drive wheel in inches × number of teeth in front chainring / number of teeth in rear sprocket.
- Metres of development = **Circumference** of drive wheel in metres × number of teeth in front chainring / number of teeth in rear cog.

Metres of development corresponds to the distance (in metres) traveled by the bicycle for one rotation of the pedals. Gear inches corresponds to the diameter of the main wheel of an old-fashioned penny-farthing bicycle with equivalent gearing. To convert from gear inches to metres of development, multiply by 0.08 (more exactly: 0.0798, or precisely: 0.0254π).

The table below shows distance traveled in metres per pedal revolution for a typical sprocket configuration on a 27 inch bicycle. Note that the two highest gears use the large front sprocket, the two lowest gears use the small front sprocket, while for all other gears, it is necessary to shift both front and rear sprockets to access the next higher or lower gear ratio. Some gears, indicated by asterisks (*) may have less favorable chain geometry due to crossover between inner and outer sprockets.

Rear hub teeth	51 tooth front outer 40 tooth front inner	
	sprocket (high)	sprocket (low)
13 (highest)	8.49 metres	6.61 metres **
15	7.33	5.75 *
17	6.46	5.06
20	5.49	4.31
24	4.58 *	3.59
28 (lowest)	3.91 **	3.08

The following table compares gear inches, metres of development, and gain ratio for 170 mm cranks and 700c wheels (diameter 70 cm). Speeds for several cadences in revolutions per minute are also given.

Gear	Gear inches	Metre development	Gain ratio	Racing	60 rpm		80 rpm		100 rpm		120 rpm	
					mph	km/h	mph	km/h	mph	km/h	mph	km/h
Higher	125	10.1	9.4	53x11	22.5	36	30	48	37.5	60	45	72
High	100	8.0	7.4	53x14	18	28.8	24	38.4	30	48	36	57.6
Med	70	5.6	5.3	53x19 or 39x15	12.7	20.2	16.9	26.9	21	33.6	25.3	40.4
Low	40	3.2	3.0	36x23	7.3	11.6	9.7	15.4	12	19.2	14.5	23.1
Lower	20	1.6	1.5	28x34	3.7	5.8	4.9	7.7	6	9.6	7.3	11.6

Only those who want to go really fast will need a gear much above 100, though gears as high as 250 have been reported for specialist racing. Cyclists who are fit and strong will find that a low gear of around 40 -50 gear-inches is quite adequate for almost all on-road use. Other cyclists may prefer a somewhat lower gear, perhaps around 20 or 30. The lowest feasible non-specialist gear (as of 2005) is around 15. Tricycles can be bought with gears as low as 8, but such low gears are not really suitable for bicycles due to the problems of balancing at very slow speeds.

As a person ages, their necessary low gear may change. Suppose a cyclist at age 40 regularly commutes by bicycle 11 miles each way without doing any other cycling or exercise. He/she might need a low gear of 45 for the 58-mile London to Brighton charity bike ride, with no need to stand on the pedals even over Ditchling Beacon. Twenty years later the same cyclist (then commuting only 5 miles each way) might need a low gear of 27 for the ride. Another five years later the same cyclist (then commuting 7 miles each way) might feel happier with a low gear of 19 for the ride.

Several gear ratio calculators are linked below. Such calculators are more useful if they show the percentage difference between gears as well as the nominal gear ratios. These calculators require the number of teeth on each gear wheel on the bicycle and the diameter of the back wheel. Standard road wheels, labeled 700c are 70 cm in diameter with the tire; the smaller 650c wheels are 65 cm in diameter. Mountain, cruiser, and most other types of wheel are 26 inches with tire.

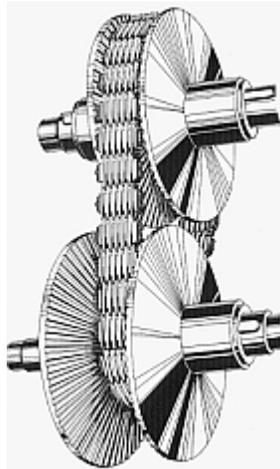
For gear ratios they also need to know the length of the pedal cranks in millimetres (crank lengths are normally some multiple of 2.5 mm). If the bicycle has an enclosed gear system (hub or bottom bracket), then details of these gears are also needed (make and model is enough for some calculators).

Chapter 9

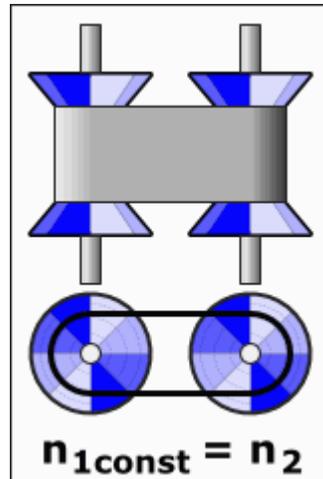
Continuously Variable Transmission

A **continuously variable transmission (CVT)** is a transmission that can change steplessly through an infinite number of effective gear ratios between maximum and minimum values. This contrasts with other mechanical transmissions that offer a fixed number of gear ratios. The flexibility of a CVT allows the driving shaft to maintain a constant angular velocity over a range of output velocities. This can provide better fuel economy than other transmissions by enabling the engine to run at its most efficient revolutions per minute (RPM) for a range of vehicle speeds. Alternatively it can be used to maximize the performance of a vehicle by allowing the engine to turn at the RPM at which it produces peak power. This is typically higher than the RPM that achieves peak efficiency.

Uses



A Chain-driven CVT



Principle of Variator

Many small tractors for home and garden use have simple rubber belt CVTs. For example, the John Deere Gator line of small utility vehicles use a belt with a conical pulley system. They can deliver an abundance of power and can reach speeds of 10–15 mph (16–24 km/h), all without need for a clutch or shifting gears. Nearly all snowmobiles, old and new, and motorscooters use CVTs, typically the rubber belt/variable pulley variety.

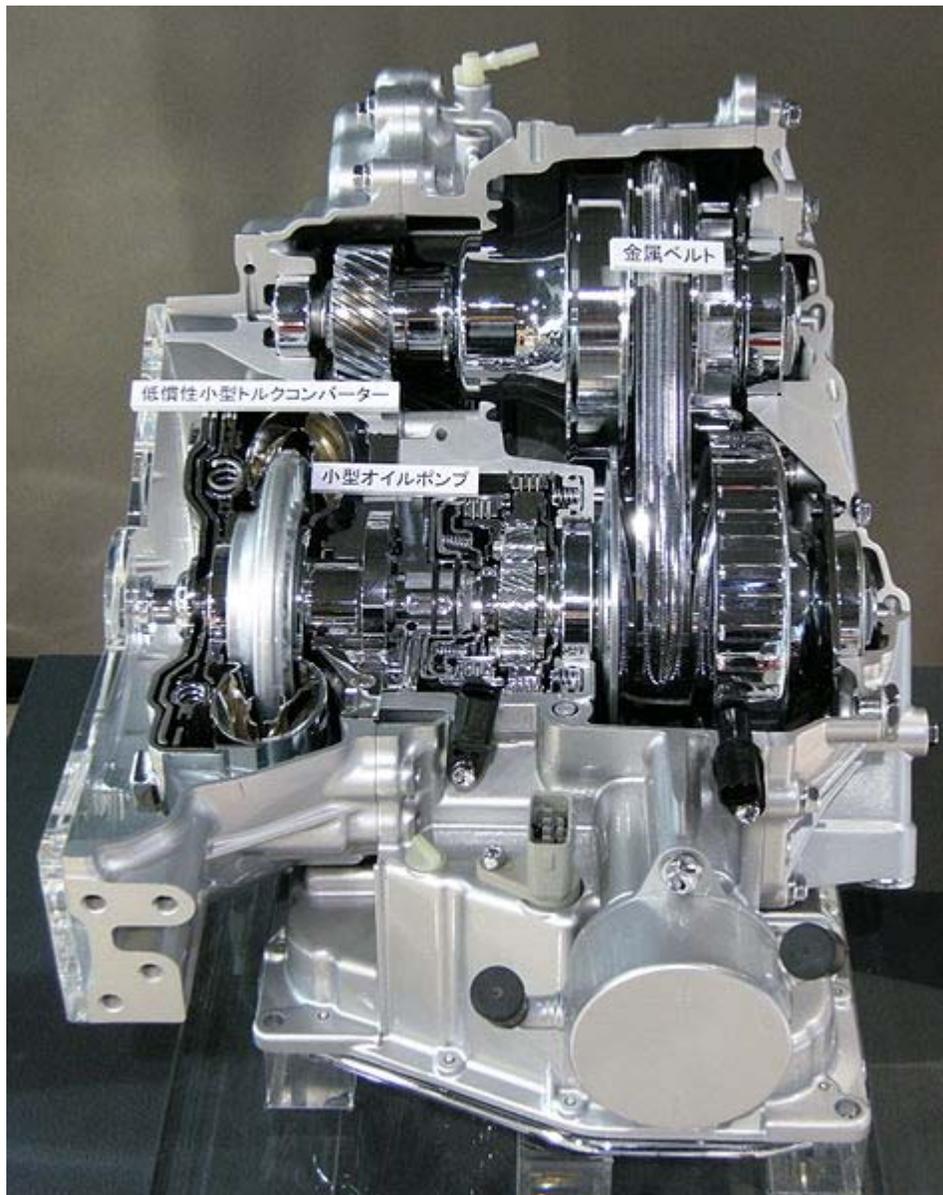
Some combine harvesters have CVTs. The CVT allows the forward speed of the combine to be adjusted independently of the engine speed. This allows the operator to slow or accelerate as needed to accommodate variations in thickness of the crop.

CVTs have been used in aircraft electrical power generating systems since the 1950s and in Sports Car Club of America (SCCA) Formula 500 race cars since the early 1970s. CVTs were banned from Formula 1 in 1994 because they were making the cars too fast. More recently, CVT systems have been developed for go-karts and have proven to increase performance and engine life expectancy. The Tomcar range of off-road vehicles also utilizes the CVT system.

Some drill presses and milling machines contain a pulley-based CVT where the output shaft has a pair of manually-adjustable conical pulley halves through which a wide drive belt from the motor loops. The pulley on the motor, however, is usually fixed in diameter, or may have a series of given-diameter steps to allow a selection of speed ranges. A handwheel on the drill press, marked with a scale corresponding to the desired machine speed, is mounted to a reduction gearing system for the operator to precisely control the width of the gap between the pulley halves. This gap width thus adjusts the gearing ratio between the motor's fixed pulley and the output shaft's variable pulley, changing speed of the chuck. A tensioner pulley is implemented in the belt transmission to take up or release the slack in the belt as the speed is altered. In most cases the speed must be changed with the motor running.

CVTs should be distinguished from Power Sharing Transmissions (PSTs), as used in newer hybrid cars, such as the Toyota Prius, Highlander and Camry, the Nissan Altima, and newer-model Ford Escape Hybrid SUVs. CVT technology uses only one input from a prime mover, and delivers variable output speeds and torque; whereas PST technology uses two prime mover inputs, and varies the ratio of their contributions to output speed and power. These transmissions are fundamentally different. However the Mitsubishi Lancer, Honda Insight and Honda CR-Z hybrids, the Nissan Tiida/Versa (only the SL model), Nissan Cube, Juke, Rogue, Altima, Murano, Maxima, Jeep Patriot and Compass use CVT.

Types



Toyota Super CVT - i

Variable-diameter pulley (VDP) or Reeves drive

In this most common CVT system, there are two V-belt pulleys that are split perpendicular to their axes of rotation, with a V-belt running between them. The gear ratio is changed by moving the two sections of one pulley closer together and the two sections of the other pulley farther apart. Due to the V-shaped cross section of the belt, this causes the belt to ride higher on one pulley and lower on the other. Doing this changes the effective diameters of the pulleys, which in turn changes the overall gear ratio. The distance between the pulleys does not change, and neither does the length of the belt, so changing the gear ratio means both pulleys must be adjusted (one bigger, the other smaller) simultaneously in order to maintain the proper amount of tension on the belt.

The V-belt needs to be very stiff in the pulley's axial direction in order to make only short radial movements while sliding in and out of the pulleys. This can be achieved by a chain and not by homogeneous rubber. To dive out of the pulleys one side of the belt must push. This again can be done only with a chain. Each element of the chain has conical sides, which perfectly fit to the pulley if the belt is running on the outermost radius. As the belt moves into the pulleys the contact area gets smaller. The contact area is proportional to the number of elements, thus the chain has lots of very small elements. The shape of the elements is governed by the static of a column. The pulley-radial thickness of the belt is a compromise between maximum gear ratio and torque. For the same reason the axis between the pulleys is as thin as possible. A film of lubricant is applied to the pulleys. It needs to be thick enough so that the pulley and the belt never touch and it must be thin in order not to waste power when each element dives into the lubrication film. Additionally, the chain elements stabilize about 12 steel bands. Each band is thin enough so that it bends easily. If bending, it has a perfect conical surface on its side. In the stack of bands each band corresponds to a slightly different gear ratio, and thus they slide over each other and need oil between them. Also the outer bands slide through the stabilizing chain, while the center band can be used as the chain linkage.



Nissan Motors *Extroid CVT*

Toroidal or roller-based CVT (Extroid CVT)

Toroidal CVTs are made up of discs and rollers that transmit power between the discs. The discs can be pictured as two almost conical parts, point to point, with the sides dished such that the two parts could fill the central hole of a torus. One disc is the input, and the other is the output (they do not quite touch). Power is transferred from one side to the other by rollers. When the roller's axis is perpendicular to the axis of the near-conical parts, it contacts the near-conical parts at same-diameter locations and thus gives a 1:1 gear ratio. The roller can be moved along the axis of the near-conical parts, changing angle as needed to maintain contact. This will cause the roller to contact the near-conical parts at varying and distinct diameters, giving a gear ratio of something other than 1:1. Systems may be partial or full toroidal. Full toroidal systems are the most efficient design while partial toroidals may still require a torque converter, and hence lose efficiency.

Magnetic CVT

A magnetic continuous variable transmission system has been developed at the University of Sheffield in 2006 and is now (2011) commercially available. Two rotating transmission disks, each with magnets attached, synchronously revolve. A change in the radius of the magnets on each of the disks, causes a change in the transmission ratio.

Infinitely Variable Transmission (IVT)

A specific type of CVT is the infinitely variable transmission (IVT), in which the range of ratios of output shaft speed to input shaft speed includes a zero ratio that can be continuously approached from a defined "higher" ratio. A zero output speed (low gear) with a finite input speed implies an infinite input-to-output speed ratio, which can be continuously approached from a given finite input value with an IVT. *Low* gears are a reference to low ratios of output speed to input speed. This low ratio is taken to the extreme with IVTs, resulting in a "neutral", or non-driving "low" gear limit, in which the output speed is zero. Unlike neutral in a normal automotive transmission, IVT output rotation may be prevented because the backdriving (reverse IVT operation) ratio may be infinite, resulting in impossibly high backdriving torque; ratcheting IVT output may freely rotate forward, though.

The IVT dates back to before the 1930s; the original design converts rotary motion to oscillating motion and back to rotary motion using roller clutches. The stroke of the intermediate oscillations is adjustable, varying the output speed of the shaft. This original design is still manufactured today, Paul B. Pires created a more compact (radially symmetric) variation that employs a ratchet mechanism instead of roller clutches, so it doesn't have to rely on friction to drive the output. An article and sketch of this variation can be found [here](#)

Most IVTs result from the combination of a CVT with a planetary gear system (which is also known as an epicyclic gear system) which enforces an IVT output shaft rotation speed which is equal to the difference between two other speeds within the IVT. This IVT configuration uses its CVT as a continuously variable regulator (CVR) of the rotation speed of any one of the three rotators of the planetary gear system (PGS). If two of the PGS rotator speeds are the input and output of the CVR, there is a setting of the CVR that results in the IVT output speed of zero. The maximum output/input ratio can be chosen from infinite practical possibilities through selection of additional input or output gear, pulley or sprocket sizes without affecting the zero output or the continuity of the whole system. The IVT is always engaged, even during its zero output adjustment.

IVTs can in some implementations offer better efficiency when compared to other CVTs as in the preferred range of operation because most of the power flows through the planetary gear system and not the controlling CVR. Torque transmission capability can also be increased. There's also possibility to stage power splits for further increase in efficiency, torque transmission capability and better maintenance of efficiency over a wide gear ratio range.

An example of a true IVT is the SIMKINETICS SIVAT that uses a ratcheting CVR. Its CVR ratcheting mechanism contributes minimal IVT output ripple across its range of ratios.

Another example of a true IVT is the Hydristor because the front unit connected to the engine can displace from zero to 27 cubic inches per revolution forward and zero to -10

cubic inches per revolution reverse. The rear unit is capable of zero to 75 cubic inches per revolution.

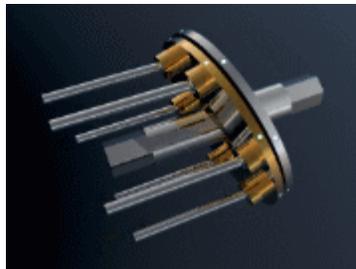
Ratcheting CVT

The ratcheting CVT is a transmission that relies on static friction and is based on a set of elements that successively become engaged and then disengaged between the driving system and the driven system, often using oscillating or indexing motion in conjunction with one-way clutches or ratchets that rectify and sum only "forward" motion. The transmission ratio is adjusted by changing linkage geometry within the oscillating elements, so that the summed maximum linkage speed is adjusted, even when the average linkage speed remains constant. Power is transferred from input to output only when the clutch or ratchet is engaged, and therefore when it is locked into a static friction mode where the driving & driven rotating surfaces momentarily rotate together without slippage.

These CVTs can transfer substantial torque, because their static friction actually increases relative to torque throughput, so slippage is impossible in properly designed systems. Efficiency is generally high, because most of the dynamic friction is caused by very slight transitional clutch speed changes. The drawback to ratcheting CVTs is vibration caused by the successive transition in speed required to accelerate the element, which must supplant the previously operating and decelerating, power transmitting element.

Ratcheting CVTs are distinguished from VDPs and roller-based CVTs by being static friction-based devices, as opposed to being dynamic friction-based devices that waste significant energy through slippage of twisting surfaces. An example of a ratcheting CVT is one prototyped as a bicycle transmission protected under U.S. Patent 5,516,132 in which strong pedalling torque causes this mechanism to react against the spring, moving the ring gear/chainwheel assembly toward a concentric, lower gear position. When the pedaling torque relaxes to lower levels, the transmission self-adjusts toward higher gears, accompanied by an increase in transmission vibration.

Hydrostatic CVTs



Honda DN-01 motorcycle



Japanese Type10 tank uses Hydraulic Mechanical Transmission (HMT).

Hydrostatic transmissions use a variable displacement pump and a hydraulic motor. All power is transmitted by hydraulic fluid. These types can generally transmit more torque, but can be sensitive to contamination. Some designs are also very expensive. However, they have the advantage that the hydraulic motor can be mounted directly to the wheel hub, allowing a more flexible suspension system and eliminating efficiency losses from friction in the drive shaft and differential components. This type of transmission is relatively easy to use because all forward and reverse speeds can be accessed using a single lever.

An integrated hydrostatic transaxle (IHT) uses a single housing for both hydraulic elements and gear-reducing elements. This type of transmission, most commonly manufactured by Hydro-Gear, has been effectively applied to a variety of inexpensive and expensive versions of ridden lawn mowers and garden tractors. Many versions of riding lawn mowers and garden tractors propelled by a hydrostatic transmission are capable of pulling a reverse tine tiller and even a single bladed plow.

One class of riding lawn mower that has recently gained in popularity with consumers is zero turning radius mowers. These mowers have traditionally been powered with wheel hub mounted hydraulic motors driven by continuously variable pumps, but this design is relatively expensive. Hydro-Gear, created the first cost-effective integrated hydrostatic transaxle suitable for propelling consumer zero turning radius mowers.

Some heavy equipment may also be propelled by a hydrostatic transmission; e.g. agricultural machinery including foragers, combines, and some tractors. A variety of heavy earth-moving equipment manufactured by Caterpillar Inc., e.g. compact and small wheel loaders, track type loaders and tractors, skid-steered loaders and asphalt compactors use hydrostatic transmission. Hydrostatic CVTs are usually not used for extended duration high torque applications due to the heat that is generated by the flowing oil.

The Honda DN-01 motorcycle is the first road-going consumer vehicle with hydrostatic drive that employs a variable displacement axial piston pump with a variable-angle swashplate.

Variable toothed wheel transmission

A variable toothed wheel transmission is not a true CVT that can alter its ratio in infinite increments, but rather approaches CVT capability by having a large number of ratios, typically 49. This transmission relies on a toothed wheel positively engaged with a chain where the toothed wheel has the ability to add or subtract a tooth at a time in order to alter its ratio relative to the chain it is driving. The "toothed wheel" can take on many configurations including ladder chains, drive bars and sprocket teeth. The huge advantage of this type of CVT is that it is a positive mechanical drive and thus does not have the frictional losses and limitations of the roller-based or VDP CVT's. The challenge in this type of CVT is to add or subtract a tooth from the toothed wheel in a very precise and controlled way in order to maintain synchronized engagement with the chain. This type of transmission has the potential to change ratios under load because of the large number of ratios, resulting in the order of 3% ratio change differences between ratios, thus a clutch or torque converter is necessary only for pull-away. No CVTs of this type are in commercial use, probably because of above mentioned development challenge.

High Frictional Losses Weakness

The variator pulley of an iCVT is choked using two small choking pulleys. Here one choking pulley is positioned on the tense side of the chain of the iCVT. Hence there is a considerable load on that choking pulley, which magnitude is proportionally to the tension in its chain. Each choking pulley is pulled up by two chain segments, one chain segment to the left and one to the right of the choking pulley; here if the two chain segments are parallel to each other then the load on the choking pulley is twice the tension in the chain. But since the two chain segments are most likely not parallel to each other during operations of an iCVT, it is estimated that the load on a choking pulley is between 1 to 1.8 times of the tension of its chain.

Also, a choking pulley is very small so that its moment arm is very small. A larger moment arm reduces the force needed to rotate a pulley. For example, using a long wrench, which has a large moment arm, to open a nut requires less force than using a short wrench, which has a small moment arm. Assuming that the diameter of a choking pulley is twice the diameter of its shaft, which is a generous estimate, then the frictional

resistance force at the outer diameter of a chocking pulley is half the frictional resistance force at the shaft of a chocking pulley.

Shock and Durability Weakness

The transmission ratio of an iCVT has to be changed one increment within less than one full rotation of its variator pulley. Has to be changed one increment means that the transmission diameter of the variator pulley has to be changed from a diameter that has a circumferential length that is equal to an integer number of teeth to another diameter that has a circumferential length that is equal to an integer number of teeth; such as changing the transmission diameter of the variator pulley from a diameter that has a circumferential length of 7 teeth to a diameter that has a circumferential length of 8 teeth for example. This is because if the transmission diameter of the variator pulley does not have a circumferential length that is equal to an integer number of teeth, such as a circumferential length of $7\frac{1}{2}$ teeth for example, improper engagement between the teeth of the variator pulley and its chain will occur. For example, imagine having a bicycle pulley with $7\frac{1}{2}$ teeth; here improper engagement between the bicycle pulley and its chain will occur when the tooth behind the $\frac{1}{2}$ tooth space is about to engage with its chain, since it is positioned a distance of $\frac{1}{2}$ tooth to late relative to its chain.

Regarding the previous paragraph, the chain of an iCVT forms an open loop on its variator pulley that partially covers its variator pulley such that an open section, which is not covered by the chain, exist. This is similar to a sprocket of a bicycle where there is a section of the sprocket that is covered by its chain, and a section of the sprocket that is not covered by its chain. During one complete rotation, the toothed section of the variator pulley of an iCVT passes by the open section and re-engages with the chain. Here if the transmission diameter of the variator pulley does not represent an integer number of teeth, improper re-engagement between the teeth of the variator pulley and its chain will occur. Also, the transmission diameter of the variator pulley cannot be changed while the toothed section of the variator pulley is covering the entire open section of its chain loop. Since this is similar to where a plate is glued across the open section of a chain loop, which does not allow expansion or contraction of the chain loop as required for transmission diameter change of the variator pulley. Therefore the transmission diameter of the variator pulley has to be changed one increment during an interval where the variator pulley rotates from an initial position where a portion of the toothed section of the variator pulley is positioned at the open section of the chain loop but not covering the entire open section, to the final position where the toothed section of the variator pulley passes by the open section of the chain loop and is about to re-engage with the chain. Since it takes less than one full rotation to rotate the variator pulley from its initial position to its final position mentioned in the previous sentence, the transmission diameter of the variator pulley has to be changed one increment within less than one full rotation.

In addition, as the transmission diameter is increased, the chain has to be pushed up the inclined surfaces of the pulley halves of the variator pulley, while the tension in the chain tends to pull the chain towards the opposite direction. Hence a large force, which is larger

than the tension in the chain, is required to change the transmission diameter. Since the transmission ratio has to be changed within less than one full rotation of the variator pulley, a large force has to be applied on the pulley halves within a very short duration. If for example the variator pulley rotates at 3600 rpm, which is equivalent to 60 revolutions per second, then the force required to change the transmission ratio has to be applied within 1/60 seconds. This would be similar to hitting something with a hammer. Therefore, here significant shock loads are applied to the variator pulley during transmission ratio change that increases the transmission diameter. These shock loads may cause comfort problem for the driver of the vehicle using an iCVT. Also an iCVT has to be designed as to be able to resist these shock loads which would most likely increase the cost and weight of an iCVT.

Torque Transfer Ability & Reliability Weakness

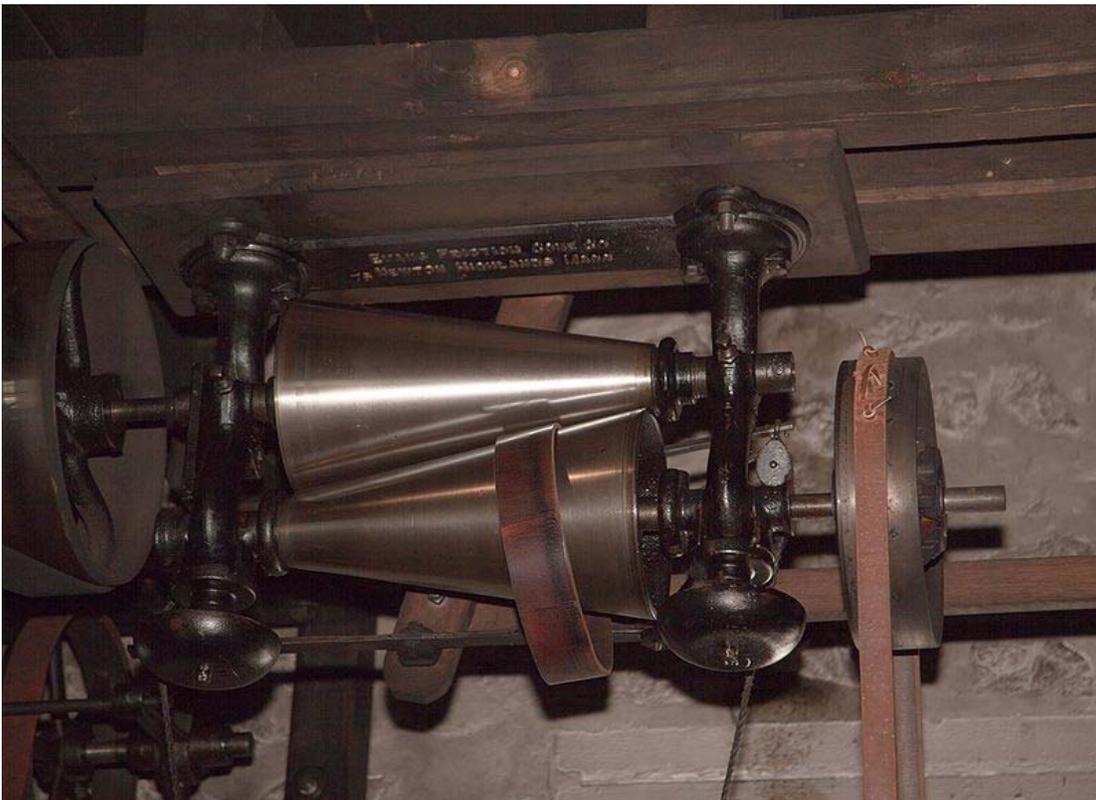
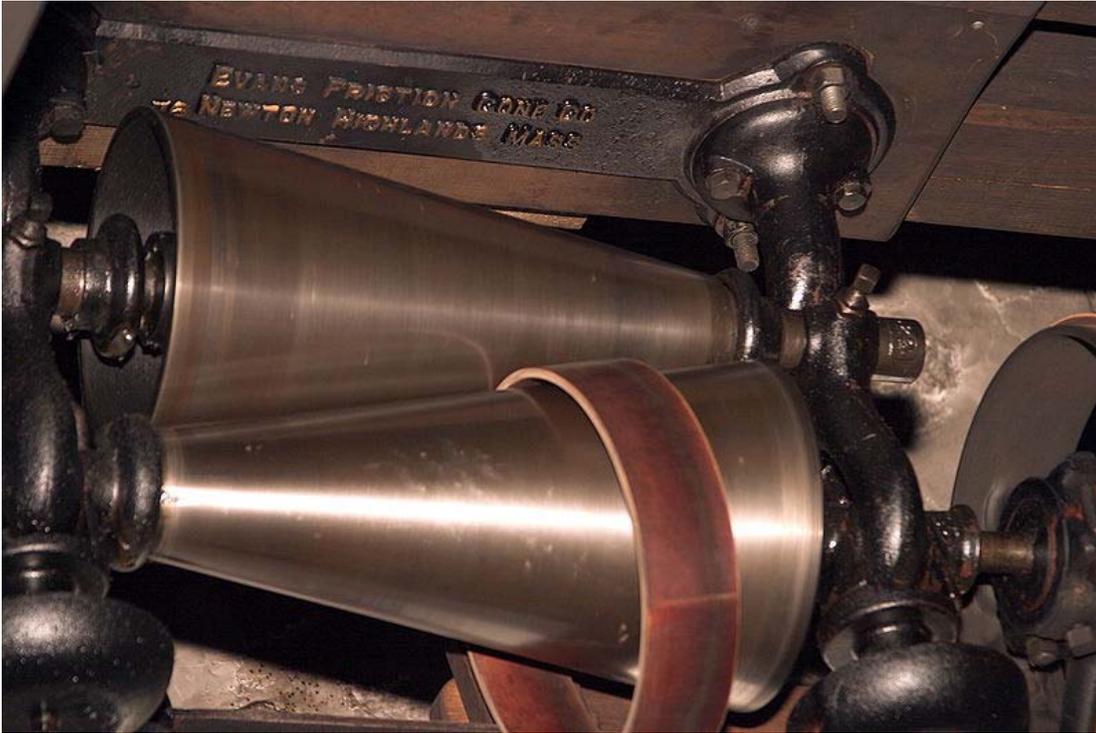
The teeth of the variator pulley of an iCVT are formed by pins that extend from one pulley half to the other pulley half and slide in the grooves of the pulley halves of the variator pulley. Here torque from the chain is transferred to the pins and then from the pins to the pulley halves. Since the pins are round and the grooves are curved, line contact between the pins and the grooves are used to transfer force from the pins to the grooves. The amount of force that can be transmitted between two parts depends on the contact area of the two parts. Since the contact areas between the pins and their grooves are very small, the amount of force that can be transmitted between them, and hence also the torque capacity of an iCVT, is limited.

Another possible problem with an iCVT is that the pins of the variator pulley can fall-out when they are not engaged with their chain. And wear of the pins and the grooves of the pulley halves can cause some serious performance and reliability problems.

Single Tooth Cone CVT

A single tooth cone CVT is one of the most promising non-friction CVT designs. Like an iCVT a single tooth cone also does not depend on friction to transmit torque; however, it does not have the weaknesses an iCVT has. A Single Tooth Cone is described in the link below:

Cone CVTs



The Evans friction cone, a type of cone CV

A cone CVT varies the effective gear ratio using one or more conical rollers. The simplest type of cone CVT, the single-cone version, uses a wheel that moves along the slope of the cone, creating the variation between the narrow and wide diameters of the cone.

In a CVT with oscillating cones, the torque is transmitted via friction from a variable number of cones (according to the torque to be transmitted) to a central, barrel-shaped hub. The side surface of the hub is convex with a specific radius of curvature which is smaller than the concavity radius of the cones. In this way, there will be only one (theoretical) contact point between each cone and the hub at any time.

A new CVT using this technology, the Warko, was presented in Berlin during the 6th International CTI Symposium of Innovative Automotive Transmissions, on December 3-7, 2007.

A particular characteristic of the Warko is the absence of a clutch: the engine is always connected to the wheels, and the rear drive is obtained by means of an epicyclic system in output. This system, named "power split", allows the engine to have a "neutral gear": when the engine turns (connected to the sun gear of the epicyclic system), the variator (i.e., the planetary gears) will compensate for the engine rotation, so the outer ring gear (which provides output) doesn't turn at all.

Radial roller CVT

The working principle of this CVT is similar to that of conventional oil compression engines, but, instead of compressing oil, common steel rollers are compressed.

The motion transmission between rollers and rotors is assisted by an adapted traction fluid, which ensures the proper friction between the surfaces and slows down wearing thereof. Unlike other systems, the radial rollers do not show a tangential speed variation (Δ) along the contact lines on the rotors. From this, a greater mechanical efficiency and working life are obtained. The main advantages of this CVT are the manufacturing inexpensiveness and the high power efficiency.

History

Leonardo da Vinci, in 1490, conceptualized a stepless continuously variable transmission. The first patent for a friction-based belt CVT was filed in Europe by Daimler and Benz in 1886, and a US Patent for a toroidal CVT was granted in 1935.

In 1910 Zenith Motorcycles built a V2-Motorcycle with the Gradua-Gear which was a CVT. This Zenith-Gradua was so successful in hillclimb events, that it was eventually barred, so that other manufacturers had a chance to win.

1912 the British motorcycle manufacturer Rudge-Whitworth built the Rudge Multigear. The Multi was a much improved version of Zenith's Gradua-Gear. The Rudge Multi was

so successful that CVT-gears were eventually barred at the famous Tourist Trophy race (which was the world's most important motorcycle race before World War I) from 1913 on.

In 1922 Browne offered a motorcycle with variable-stroke ratchet drive using a face ratchet.

An early application of CVT was in the British Clyno car, introduced in 1923.

A CVT, called Variomatic, was designed and built by Hub van Doorne, co-founder of Van Doorne's Automobiel Fabriek (DAF), in the late 1950s, specifically to produce an automatic transmission for a small, affordable car. The first DAF car using van Doorne's CVT, the DAF 600, was produced in 1958. Van Doorne's patents were later transferred to a company called VDT (Van Doorne Transmissie B.V.) when the passenger car division was sold to Volvo; its CVT was used in the Volvo 340.

Many snowmobiles use a rubber belt CVT. In 1974, Rokon offered a motorcycle with a rubber belt CVT.

CVTs are used in some ATVs. The first ATV equipped with CVT was Suzuki's LT80 mini in 1987.

In early 1987, Subaru launched the Justy in Tokyo with an electronically controlled continuously variable transmission (ECVT) developed by Fuji Heavy Industries, which owns Subaru. In 1989 the Justy became the first production car in the U.S. to offer CVT technology. While the Justy saw only limited success, Subaru continues to use CVT in its kei cars to this day, while also supplying it to other manufacturers.

In the summer of 1987 the Ford Fiesta and Fiat Uno became the first mainstream European cars to be equipped with steel-belted CVT (as opposed to the less robust rubber-belted DAF design). This CVT, the Ford CTX was developed by Ford, Van Doorne, and Fiat, with work on the transmission starting in 1976.

The 1992 Nissan March contained Nissan's N-CVT based on the Fuji Heavy Industries ECVT. In the late 1990s, Nissan designed its own CVT that allowed for higher torque and included a torque converter. This gearbox was used in a number of Japanese-market models. Nissan is also the only car maker to bring a roller-based CVT to the market in recent years. Their toroidal CVT, named the Extroid, was available in the Japanese market Y34 Nissan Gloria and V35 Skyline GT-8. However, the gearbox was not carried over when the Cedric/Gloria was replaced by the Nissan Fuga in 2004. The Nissan Murano, introduced in 2003, and the Nissan Rogue, introduced in 2007, also use CVT in their automatic transmission models. In a Nissan Press Release, July 12, 2006, Nissan announced a huge shift to CVT transmissions when they selected their XTronic CVT technology for all automatic versions of the Nissan Versa, Cube, Sentra, Altima and Maxima vehicles in North America, making the CVT a mainstream transmission system. One major motivator for Nissan to make a switch to CVTs was as a part of their 'Green

Program 2010' aimed at reducing CO2 emissions by 2010. To date Nissan has had the most success with producing their CVTs in high volume and on a wide range of vehicles. The CVT found in Nissan's Maxima, Murano and the V6 version of Altima is considered to be the worlds first "3.5L class" belt CVT and can hold much higher torque loads than other belt CVTs.

After studying pulley-based CVT for years, Honda also introduced their own version on the 1995 Honda Civic VTi. Dubbed Honda Multi Matic, this CVT gearbox accepted higher torque than traditional pulley CVTs, and also includes a torque converter for "creep" action. The CVT is also currently employed in the Honda City ZX that is manufactured in India and Honda City Vario manufactured in Pakistan.

Toyota used a Power Split Transmission (PST) in the 1997 Prius, and all subsequent Toyota and Lexus hybrids sold internationally continue to use the system (marketed under the Hybrid Synergy Drive name). The HSD is also referred to as an Electronically-controlled Continuously-variable Transmission. The PST allows either the electric motor or the internal combustion engine (ICE) or both to propel the vehicle. In ICE-only mode, part of the engine's power is mechanically coupled to the drivetrain, with the other part going through a generator and a motor. The amount of power being channeled through the electrical path determine the effective gear ratio. Toyota also offers a non-hybrid CVT called Multidrive for models such as Avensis.

Audi has, since 2000, offered a chain-type CVT (Multitronic) as an option on some of its larger-engine models, for example the A4 3.0 L V6.

Fiat in 2000 offered a Cone-type CVT as an option on its hit model Fiat Punto (16v 80 PS ELX,Sporting).

BMW used a belt-drive CVT as an option for the low- and middle-range MINI in 2001, forsaking it only on the supercharged version of the car where the increased torque levels demanded a conventional automatic gearbox. The CVT could also be manually "shifted" if desired with software-simulated shift points.

GM introduced its version of CVT known as VTi in 2002. It was used in the Saturn Vue and Saturn Ion models. This transmission was quickly withdrawn in 2005 models due to high failure rates.

Ford introduced a chain-driven CVT known as the CFT30 in their 2005 Ford Freestyle, Ford Five Hundred and Mercury Montego. The transmission was designed in cooperation with German automotive supplier ZF Friedrichshafen and was produced in Batavia, Ohio at Batavia Transmissions LLC (a subsidiary of Ford Motor Company) until March 22, 2007. The Batavia plant also produced the belt-driven CFT23 CVT which went in the Ford Focus C-MAX. Ford also sold Escort and Orion models in Europe with CVTs in the 1980s and 1990s.

Contract agreements were established in 2006 between MTD Products and Torotrak for the first full toroidal system to be manufactured for outdoor power equipment such as jet skis, ski-mobiles and ride-on mowers.

The 2007 Dodge Caliber and the related Jeep Compass and Jeep Patriot employ a CVT using a variable pulley system as their optional automatic transmission.

The 2008 Mitsubishi Lancer model is available with CVT transmission as the automatic transmission. DE and ES models receive a standard CVT with Drive and Low gears; the GTS model is equipped with a standard Drive and also a Sportronic mode that allows the driver to use 6 different preset gear ratios (either with the shifter or steering wheel-mounted paddle shifters).

The 2009 SEAT Exeo is available with a CVT automatic transmission (multitronic) as an option for the 2.0 TSI 200 hp (149 kW) petrol engine, with selectable 'six-speeds'.

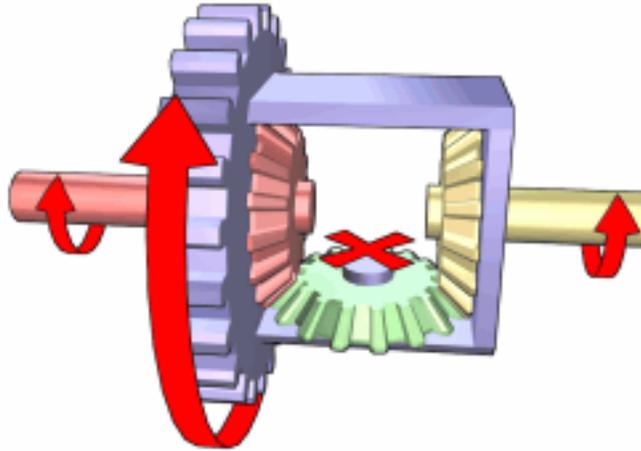
Subaru offers CVT on the 2010 Legacy and 2010 Outback (Lineartronic).

Chapter 10

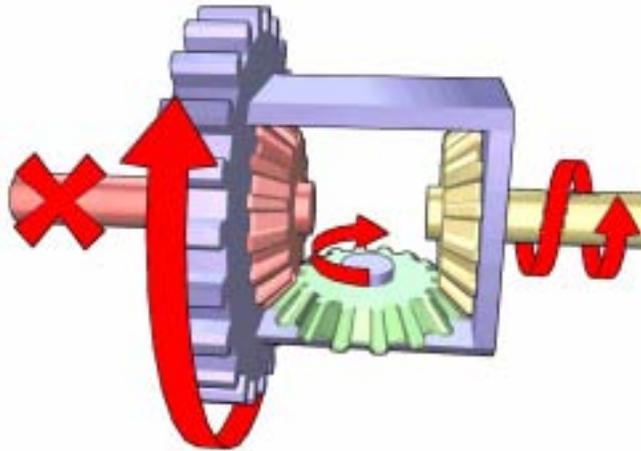
Differential (Mechanical Device)



A cutaway view of an automotive final drive unit which contains the differential



Input torque is applied to the ring gear (blue), which turns the entire carrier (blue). The carrier is connected to both the side gears (red and yellow) only through the planet gear (green) (visual appearances in the diagram notwithstanding). Torque is transmitted to the side gears through the planet gear. The planet gear revolves around the axis of the carrier, driving the side gears. If the resistance at both wheels is equal, the planet gear revolves without spinning about its own axis, and both wheels turn at the same rate.



If the left side gear (red) encounters resistance, the planet gear (green) spins as well as revolving, allowing the left side gear to slow down, with an equal speeding up of the right side gear (yellow).

A **differential** is a device, usually but not necessarily employing gears, capable of transmitting torque and rotation through three shafts, almost always used in one of two ways: in one way, it receives one input and provides two outputs—this is found in most automobiles—and in the other way, it combines two inputs to create an output that is the sum, difference, or average, of the inputs.

In automobiles and other wheeled vehicles, the differential allows each of the driving roadwheels to rotate at different speeds, while for most vehicles supplying equal torque to each of them.

Purpose

A vehicle's wheels rotate at different speeds, mainly when turning corners. The differential is designed to drive a pair of wheels with equal torque while allowing them to rotate at different speeds. In vehicles without a differential, such as karts, both driving wheels are forced to rotate at the same speed, usually on a common axle driven by a simple chain-drive mechanism. When cornering, the inner wheel needs to travel a shorter distance than the outer wheel, so with no differential, the result is the inner wheel spinning and/or the outer wheel dragging, and this results in difficult and unpredictable handling, damage to tires and roads, and strain on (or possible failure of) the entire drivetrain.

History

There are many claims to the invention of the differential gear but it is likely that it was known, at least in some places, in ancient times. Some historical milestones of the differential include:

- 1050 BC–771 BC: The *Book of Song* (which itself was written between 502 and 557 A.D.) makes the assertion that the South Pointing Chariot, which uses a differential gear, was invented during the Western Zhou Dynasty in China.
- 30 BC - 20 BC: Differential gear systems used in China and on the Greek island of Antikythera
- 227–239 AD: Despite doubts from fellow ministers at court, Ma Jun from the Kingdom of Wei in China invents the first historically verifiable South Pointing Chariot, which provided cardinal direction as a non-magnetic, mechanized compass.
- 658, 666 AD: two Chinese Buddhist monks and engineers create South Pointing Chariots for Emperor Tenji of Japan.
- 1027, 1107 AD: Documented Chinese reproductions of the South Pointing Chariot by Yan Su and then Wu Deren, which described in detail the mechanical functions and gear ratios of the device much more so than earlier Chinese records.
- 1720: Joseph Williamson uses a differential gear in a clock.
- 1810: Rudolph Ackermann of Germany invents a four-wheel steering system for carriages, which some later writers mistakenly report as a differential.
- 1827: modern automotive differential patented by watchmaker Onésiphore Pecqueur (1792–1852) of the *Conservatoire des Arts et Métiers* in France for use on a steam cart. (Sources: Britannica Online and)
- 1832: Richard Roberts of England patents 'gear of compensation', a differential for road locomotives.
- 1876: James Starley of Coventry invents chain-drive differential for use on bicycles; invention later used on automobiles by Karl Benz.

- 1897: first use of differential on an Australian steam car by David Shearer.
- 1913: Packard introduces the spiral-gear differential, which cuts gear noise.
- 1926: Packard introduces the hypoid differential, which enables the propeller shaft and its hump in the interior of the car to be lowered.
- 1958: Vernon Gleasman patents the Torsen dual-drive differential, a type of limited slip differential that relies solely on the action of gearing instead of a combination of clutches and gears.

Functional description



A cutaway drawing of a car's rear axle, showing the crown wheel and pinion of the final drive, and the smaller differential gears

The following description of a differential applies to a "traditional" rear-wheel-drive car or truck with an "open" or limited slip differential:

Torque is supplied from the engine, via the transmission, to a drive shaft (British term: 'propeller shaft', commonly and informally abbreviated to 'prop-shaft'), which runs to the final drive unit that contains the differential. A spiral bevel pinion gear takes its drive from the end of the propeller shaft, and is encased within the housing of the final drive unit. This meshes with the large spiral bevel *ring* gear, known as the crown wheel. The crown wheel and pinion may mesh in hypoid orientation, not shown. The crown wheel gear is attached to the differential *carrier* or cage, which contains the 'sun' and 'planet' wheels or gears, which are a cluster of four opposed bevel gears in perpendicular plane,

so each bevel gear meshes with two neighbours, and rotates counter to the third, that it faces and does not mesh with. The two sun wheel gears are aligned on the same axis as the crown wheel gear, and drive the axle half shafts connected to the vehicle's driven wheels. The other two planet gears are aligned on a perpendicular axis which changes orientation with the ring gear's rotation. In the two figures shown above, only one planet gear (green) is illustrated, however, most automotive applications contain two opposing planet gears. Other differential designs employ different numbers of planet gears, depending on durability requirements. As the differential carrier rotates, the changing axis orientation of the planet gears imparts the motion of the ring gear to the motion of the sun gears by pushing on them rather than turning against them (that is, the same teeth stay in the same mesh or contact position), but because the planet gears are not restricted from turning against each other, *within* that motion, the sun gears can counter-rotate relative to the ring gear and to each other under the same force (in which case the same teeth do not stay in contact).

Thus, for example, if the car is making a turn to the right, the main crown wheel may make 10 full rotations. During that time, the left wheel will make more rotations because it has further to travel, and the right wheel will make fewer rotations as it has less distance to travel. The sun gears (which drive the axle half-shafts) will rotate in opposite directions relative to the ring gear by, say, 2 full turns each (4 full turns relative to each other), resulting in the left wheel making 12 rotations, and the right wheel making 8 rotations.

The rotation of the crown wheel gear is always the average of the rotations of the side sun gears. This is why, if the driven roadwheels are lifted clear of the ground with the engine off, and the drive shaft is held (say leaving the transmission 'in gear', preventing the ring gear from turning inside the differential), manually rotating one driven roadwheel causes the opposite roadwheel to rotate in the opposite direction by the same amount.

When the vehicle is traveling in a straight line, there will be no differential movement of the planetary system of gears other than the minute movements necessary to compensate for slight differences in wheel diameter, undulations in the road (which make for a longer or shorter wheel path), etc.

Loss of traction

One undesirable side effect of a conventional differential is that it can limit traction under less than ideal conditions. The amount of traction required to propel the vehicle at any given moment depends on the load at that instant—how heavy the vehicle is, how much drag and friction there is, the gradient of the road, the vehicle's momentum, and so on.

The torque applied to each driving wheel is a result of the engine, transmission and drive axles applying a twisting force against the resistance of the traction at that roadwheel. In lower gears and thus at lower speeds, and unless the load is exceptionally high, the drivetrain can *supply* as much torque as necessary, so the limiting factor becomes the traction under each wheel. It is therefore convenient to define traction as the amount of

torque that can be generated between the tire and the road surface, before the wheel starts to slip. If the torque applied to drive wheels does not exceed the threshold of traction, the vehicle will be propelled in the desired direction; if not, then one or more wheels will simply spin.

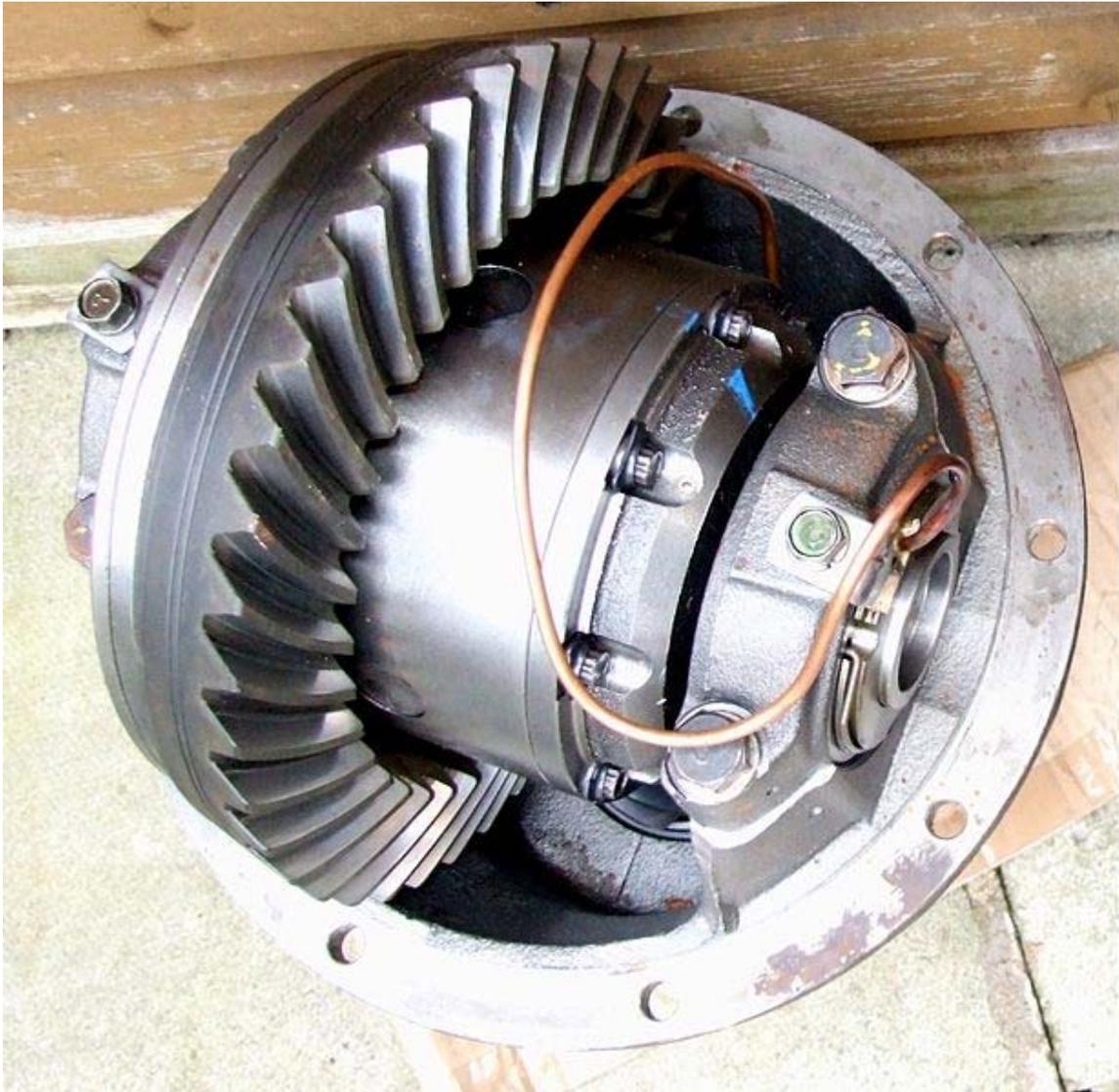
To illustrate how a conventional "open" (non-locked or otherwise traction-aided) differential can limit torque applied to the driving wheels, imagine a simple rear-wheel drive vehicle, with one rear roadwheel on asphalt with good grip, and the other on a patch of slippery ice. Based on the load, gradient, etcetera, the vehicle requires a certain amount of torque applied to the drive wheels to move forward. If the two roadwheels were connected together without a differential, each roadwheel would be supplied with an equal amount of torque, and would push against the road surface as hard as possible. The roadwheel on ice would quickly reach the limit of traction, but would be unable to spin because the other roadwheel to which it is connected to has good traction. Therefore, when the good traction of the asphalt plus the poor traction from the ice together exceed the minimum required for forward propulsion, the vehicle accelerates.

With an open differential, however, where each tire is allowed to rotate at different speeds, as soon as the tire atop the ice patch exceeds the threshold of traction available to it, it will begin to spin or "slip". Additionally, once the traction threshold is broken and the tire experiences slip, the traction available will also decrease in accordance to the laws of kinetic friction. Since an open differential limits total torque applied to both drive wheels to the amount utilized by the lower traction wheel multiplied by a factor of 2, when one wheel is on a slippery surface, the total torque applied to the driving wheels will be lower than the minimum torque required for vehicle propulsion. Thus, the vehicle will not be propelled.

A proposed way to distribute the power to the wheels, is to use the concept of **gearless** differential, of which a review has been reported by Provatidis , but the various configurations seem to correspond either to the "sliding pins and cams" type, such as the ZF B-70 available for early VWs, or are a variation of the ball differential.

Many newer vehicles feature traction control, which partially mitigates the poor traction characteristics of an open differential by using the anti-lock braking system to limit or stop the slippage of the low traction wheel, thus transferring more torque to the wheel with good traction. While not as effective in propelling a vehicle under poor traction conditions as a traction-aided differential, it is better than a simple mechanical open differential with no electronic traction assistance.

Traction-aiding devices



ARB, Air Locking Differential

There are various devices for getting more usable traction from vehicles with differentials.

- One solution is the Positive Traction (Posi), the most well-known of which is the clutch-type. With this differential, the side gears are coupled to the carrier via a multi-disc clutch which allows extra torque to be sent to the wheel with higher resistance than available at the other driven roadwheel when the limit of friction is reached at that other wheel. Below the limit of friction more torque goes to the slower (inside) wheel.
- A limited slip differential (LSD) or anti-spin is another type of traction aiding device that uses a mechanical system that activates under centrifugal force to

positively lock the left and right spider gears together when one wheel spins a certain amount faster than the other. This type behaves as an open differential unless one wheel begins to spin and exceeds that threshold. While positraction units can be of varying strength, some of them with high enough friction to cause an inside tire to spin or outside tire to drag in turns like a spooled differential, the LSD will remain open unless enough torque is applied to cause one wheel to lose traction and spin, at which point it will engage. A LSD can use clutches like a posi when engaged, or may also be a solid mechanical connection like a locker or spool. It is called limited slip because it does just that; it limits the amount that one wheel can "slip" (spin).

- A locking differential, such as ones using differential gears in normal use but using air or electrically controlled mechanical system, which when locked allow no difference in speed between the two wheels on the axle. They employ a mechanism for allowing the axles to be locked relative to each other, causing both wheels to turn at the same speed regardless of which has more traction; this is equivalent to effectively bypassing the differential gears entirely. Other locking systems may not even use differential gears but instead drive one wheel or both depending on torque value and direction. Automatic mechanical lockers do allow for some differentiation under certain load conditions, while a selectable locker typically couples both axles with a solid mechanical connection like a spool when engaged.
- A high-friction 'Automatic Torque Biasing' (ATB) differential, such as the Torsen differential, where the friction is between the gear teeth rather than at added clutches. This applies more torque to the driven roadwheel with highest resistance (grip or traction) than is available at the other driven roadwheel when the limit of friction is reached at that other wheel. When tested with the wheels off the ground, if one wheel is rotated with the differential case held, the other wheel will still rotate in the opposite direction as for an open differential but there will be some frictional losses and the torque will be distributed at other than 50/50. Although marketed as being "torque-sensing", it functions the same as a limited slip differential.
- A very high-friction differential, such as the ZF "sliding pins and cams" type, so that there is locking from very high internal friction. When tested with the wheels off the ground with torque applied to one wheel it will lock, but it is still possible for the differential action to occur in use, albeit with considerable frictional losses, and with the road loads at each wheel in opposite directions rather than the same (acting with a "locking and releasing" action rather than a distributed torque).
- Electronic traction control systems usually use the anti-lock braking system (ABS) roadwheel speed sensors to detect a spinning roadwheel, and apply the brake to that wheel. This progressively raises the reaction torque at that roadwheel, and the differential compensates by transmitting more torque through

the other roadwheel—the one with better traction. In Volkswagen Group vehicles, this specific function is called 'Electronic Differential Lock' (EDL).

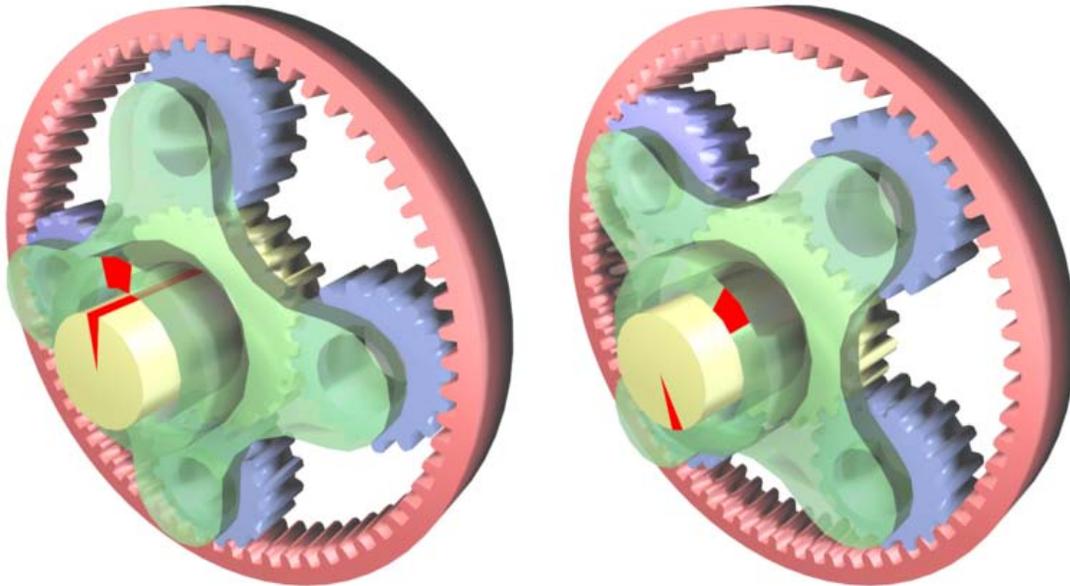
- A Spool is just what it sounds like. It may replace the spider gears within the differential carrier, or the entire carrier. A spool locks both axle shafts together 100% for maximum traction. This is typically only used in drag racing applications, where the vehicle is to be driven in a straight line while applying tremendous torque to both wheels.
- In a four-wheel drive vehicle, a viscous coupling unit can replace a centre differential entirely, or be used to limit slip in a conventional 'open' differential. It works on the principle of allowing the two output shafts to counter-rotate relative to each other, by way of a system of slotted plates that operate within a viscous fluid, often silicone. The fluid allows slow relative movements of the shafts, such as those caused by cornering, but will strongly resist high-speed movements, such as those caused by a single wheel spinning. This system is similar to a limited slip differential.

A four-wheel drive (4WD) vehicle will have at least two differentials (one in each axle for each pair of driven roadwheels), and possibly a centre differential to apportion torque between the front and rear axles. In some cases (e.g. Lancia Delta Integrale, Porsche 964 Carrera 4 of 1989) the centre differential is an epicyclic differential to divide the torque asymmetrically, but at a fixed rate between the front and rear axle. Other methods utilise an 'Automatic Torque Biasing' (ATB) centre differential, such as a Torsen—which is what Audi use in their quattro cars (with longitudinal engines).

4WD vehicles without a centre differential should not be driven on dry, paved roads in four-wheel drive mode, as small differences in rotational speed between the front and rear wheels cause a torque to be applied across the transmission. This phenomenon is known as "wind-up", and can cause considerable damage to the transmission or drive train. On loose surfaces these differences are absorbed by the tire slippage on the road surface.

A transfer case may also incorporate a centre differential, allowing the drive shafts to spin at different speeds. This permits the four-wheel drive vehicle to drive on paved surfaces without experiencing "wind-up".

Epicyclic differential



Epicyclic gearing is used here to apportion torque asymmetrically. The input shaft is the green hollow one, the yellow is the low torque output, and the pink is the high torque output. The force applied in the yellow and the pink gears is the same, but since the arm of the pink one is $2\times$ to $3\times$ as big, the torque will be $2\times$ to $3\times$ as high.

An epicyclic differential uses epicyclic gearing to split and apportion torque asymmetrically between the front and rear axles. An epicyclic differential is at the heart of the Toyota Prius automotive drive train, where it interconnects the engine, motor-generators, and the drive wheels (which have a second differential for splitting torque as usual). It has the advantage of being relatively compact along the length of its axis (that is, the sun gear shaft).

Epicyclic gears are also called planetary gears because the axes of the planet gears revolve around the common axis of the sun and ring gears that they mesh with and roll between. In the image, the yellow shaft carries the sun gear which is almost hidden. The blue gears are called planet gears and the pink gear is the ring gear or annulus.

Spur-gear differential

This is another type of differential that was used in some early automobiles, more recently the Oldsmobile Toronado, as well as other non-automotive applications. It consists of spur gears only.

A spur-gear differential has two equal-sized spur gears, one for each half-shaft, with a space between them. Instead of the Bevel gear, also known as a miter gear, assembly (the "spider") at the centre of the differential, there is a rotating carrier on the same axis as the

two shafts. Torque from a prime mover or transmission, such as the drive shaft of a car, rotates this carrier.

Mounted in this carrier are one or more pairs of identical pinions, generally longer than their diameters, and typically smaller than the spur gears on the individual half-shafts. Each pinion pair rotates freely on pins supported by the carrier. Furthermore, the pinions pairs are displaced axially, such that they mesh only for the part of their length between the two spur gears, and rotate in opposite directions. The remaining length of a given pinion meshes with the nearer spur gear on its axle. Therefore, each pinion couples that spur gear to the other pinion, and in turn, the other spur gear, so that when the drive shaft rotates the carrier, its relationship to the gears for the individual wheel axles is the same as that in a bevel-gear differential.

Non-automotive applications

A differential gear train can also be used to allow a difference between two input axles. Mills often used such gears to apply torque in the required axis. It's also used in fine mechanical watches with a hand to show the amount of reserve power in the mainspring.

The oldest known example of a differential was once thought to be in the Antikythera mechanism. It was supposed to have used such a train to produce the difference between two inputs, one input related to the position of the sun on the zodiac, and the other input related to the position of the moon on the zodiac; the output of the differential gave a quantity related to the moon's phase. It has now been proven that the assumption of the existence of a differential gearing arrangement was incorrect.

Chinese South Pointing Chariots may also have been very early applications of differentials. The chariot had a pointer which constantly pointed to the south, no matter how the chariot turned as it travelled. It could therefore be used as a type of compass. It is widely thought that some sort of differential mechanism responded to any difference in the numbers of rotations that the two wheels of the chariot made, and turned the pointer appropriately. However, there is considerable uncertainty about this.

In the first half of the twentieth century, mechanical analog computers, called differential analyzers, were constructed that used differential gear trains to perform addition and subtraction. The U.S. Navy Mk.1 gun fire control computer used about 160 differentials of the bevel-gear type.

Differentials, usually flat but also spherical, are used in wristwatches to allow the power reserve to be indicated. Power from the mainspring is split via the differential to the time indications and the power reserve indicator. Differentials are also used in watchmaking to link two separate regulating systems with the aim of averaging out errors. Greubel Forsey use a spherical differential to link two double tourbillon systems in their Quadruple Differential Tourbillon.

Active differentials

A relatively new technology is the electronically-controlled 'active differential'. An electronic control unit (ECU) uses inputs from multiple sensors, including yaw rate, steering input angle, and lateral acceleration—and adjusts the distribution of torque to compensate for undesirable handling behaviours like understeer. Active differentials used to play a large role in the World Rally Championship, but in the 2006 season the FIA has limited the use of active differentials only to those drivers who have not competed in the World Rally Championship in the last five years.

Fully integrated active differentials are used on the Ferrari F430, Mitsubishi Lancer Evolution, and on the rear wheels in the Acura RL. A version manufactured by ZF is also being offered on the latest Audi S4 and Audi A4.

The second constraint of the differential is passive—it is actuated by the friction kinematics chain through the ground. The difference in torque on the roadwheels and tires (caused by turns or bumpy ground) drives the second degree of freedom, (overcoming the torque of inner friction) to equalise the driving torque on the tires. The sensitivity of the differential depends on the inner friction through the second degree of freedom. All of the differentials (so called “active” and “passive”) use clutches and brakes for restricting the second degree of freedom, so all suffer from the same disadvantage—decreased sensitivity to a dynamically changing environment. The sensitivity of the ECU controlled differential is also limited by the time delay caused by sensors and the response time of the actuators.

Chapter 11

Transmission (Mechanics)

A **transmission** or **gearbox** provides speed and torque conversions from a rotating power source to another device using gear ratios. In British English the term transmission refers to the whole drive train, including gearbox, clutch, prop shaft (for rear-wheel drive), differential and final drive shafts. In American English, however, the distinction is made that a gearbox is any device which converts speed and torque, whereas a transmission is a type of gearbox that can be "shifted" to dynamically change the speed:torque ratio, such as in a vehicle. The most common use is in motor vehicles, where the transmission adapts the output of the internal combustion engine to the drive wheels. Such engines need to operate at a relatively high rotational speed, which is inappropriate for starting, stopping, and slower travel. The transmission reduces the higher engine speed to the slower wheel speed, increasing torque in the process. Transmissions are also used on pedal bicycles, fixed machines, and anywhere else rotational speed and torque needs to be adapted.

Often, a transmission will have multiple gear ratios (or simply "gears"), with the ability to switch between them as speed varies. This switching may be done manually (by the operator), or automatically. Directional (forward and reverse) control may also be provided. Single-ratio transmissions also exist, which simply change the speed and torque (and sometimes direction) of motor output.

In motor vehicle applications, the transmission will generally be connected to the crankshaft of the engine. The output of the transmission is transmitted via driveshaft to one or more differentials, which in turn drive the wheels. While a differential may also provide gear reduction, its primary purpose is to change the direction of rotation.

Conventional gear/belt transmissions are not the only mechanism for speed/torque adaptation. Alternative mechanisms include torque converters and power transformation (e.g., diesel-electric transmission, hydraulic drive system, etc.). Hybrid configurations also exist.

Explanation



The main gearbox of a Bristol Sycamore helicopter

Early transmissions included the right-angle drives and other gearing in windmills, horse-powered devices, and steam engines, in support of pumping, milling, and hoisting.

Most modern gearboxes are used to increase torque while reducing the speed of a prime mover output shaft (e.g. a motor crankshaft). This means that the output shaft of a gearbox will rotate at slower rate than the input shaft, and this reduction in speed will produce a mechanical advantage, causing an increase in torque. A gearbox can be setup to do the opposite and provide an increase in shaft speed with a reduction of torque. Some of the simplest gearboxes merely change the physical direction in which power is transmitted.

Many typical automobile transmissions include the ability to select one of several different gear ratios. In this case, most of the gear ratios (often simply called "gears") are used to slow down the output speed of the engine and increase torque. However, the highest gears may be "overdrive" types that increase the output speed.

Uses

Gearboxes have found use in a wide variety of different—often stationary—applications, such as wind turbines.

Transmissions are also used in agricultural, industrial, construction, mining and automotive equipment. In addition to ordinary transmission equipped with gears, such equipment makes extensive use of the hydrostatic drive and electrical adjustable-speed drives.

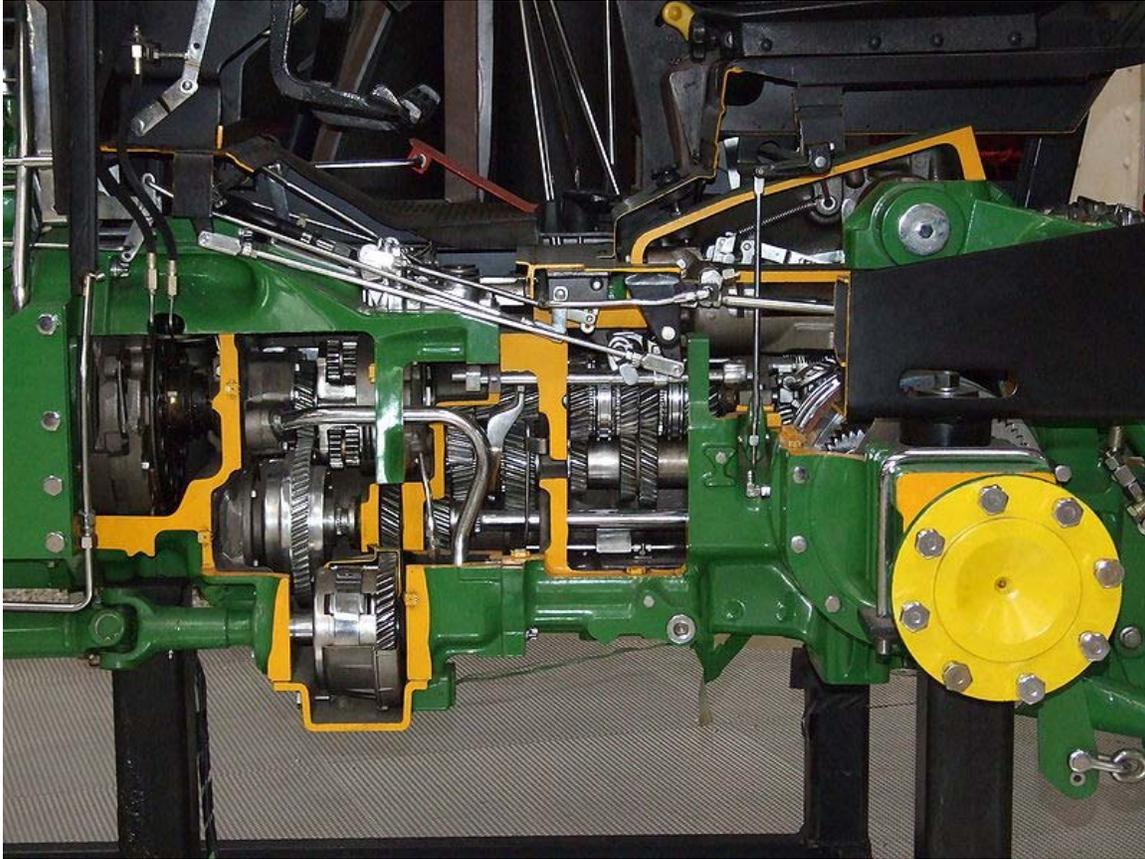
Simple

The simplest transmissions, often called gearboxes to reflect their simplicity (although complex systems are also called gearboxes in the vernacular), provide gear reduction (or, more rarely, an increase in speed), sometimes in conjunction with a right-angle change in direction of the shaft. These are often used on PTO-powered agricultural equipment, since the axial PTO shaft is at odds with the usual need for the driven shaft, which is either vertical (as with rotary mowers), or horizontally extending from one side of the implement to another (as with manure spreaders, flail mowers, and forage wagons). More complex equipment, such as silage choppers and snowblowers, have drives with outputs in more than one direction.

The gearbox in a wind turbine converts the slow, high-torque rotation of the turbine into much faster rotation of the electrical generator. These are much larger and more complicated than the PTO gearboxes in farm equipment. They weigh several tons and typically contain three stages to achieve an overall gear ratio from 40:1 to over 100:1, depending on the size of the turbine. (For aerodynamic and structural reasons, larger turbines have to turn more slowly, but the generators all have to rotate at similar speeds of several thousand rpm.) The first stage of the gearbox is usually a planetary gear, for compactness, and to distribute the enormous torque of the turbine over more teeth of the low-speed shaft. Durability of these gearboxes has been a serious problem for a long time.

Regardless of where they are used, these simple transmissions all share an important feature: the gear ratio cannot be changed during use. It is fixed at the time the transmission is constructed.

Multi-ratio systems



Tractor transmission with 16 forward and 8 backward gears

Many applications require the availability of multiple gear ratios. Often, this is to ease the starting and stopping of a mechanical system, though another important need is that of maintaining good fuel efficiency.

Automotive basics

The need for a transmission in an automobile is a consequence of the characteristics of the internal combustion engine. Engines typically operate over a range of 600 to about 7000 revolutions per minute (though this varies, and is typically less for diesel engines), while the car's wheels rotate between 0 rpm and around 1800 rpm.

Furthermore, the engine provides its highest torque outputs approximately in the middle of its range, while often the greatest torque is required when the vehicle is moving from rest or traveling slowly. Therefore, a system that transforms the engine's output so that it can supply high torque at low speeds, but also operate at highway speeds with the motor still operating within its limits, is required. Transmissions perform this transformation.

Many transmissions and gears used in automotive and truck applications are contained in a cast iron case, though more frequently aluminium is used for lower weight especially in cars. There are usually three shafts: a mainshaft, a countershaft, and an idler shaft.

The mainshaft extends outside the case in both directions: the input shaft towards the engine, and the output shaft towards the rear axle (on rear wheel drive cars- front wheel drives generally have the engine and transmission mounted transversely, the differential being part of the transmission assembly.) The shaft is suspended by the main bearings, and is split towards the input end. At the point of the split, a pilot bearing holds the shafts together. The gears and clutches ride on the mainshaft, the gears being free to turn relative to the mainshaft except when engaged by the clutches.

Types of automobile transmissions include manual, automatic or semi-automatic transmission.

Manual



A five-speed gearbox.

Manual transmission come in two basic types:

- a simple but rugged **sliding-mesh** or unsynchronized / non-synchronous system, where straight-cut spur gear sets are spinning freely, and must be synchronized by the operator matching engine revs to road speed, to avoid noisy and damaging "gear clash",

- and the now common **constant-mesh** gearboxes which can include non-synchronised, or synchronized / synchromesh systems, where diagonal cut helical (and sometimes double-helical) gear sets are constantly "meshed" together, and a dog clutch is used for changing gears. On synchromesh boxes, friction cones or "synchro-rings" are used in addition to the dog clutch.

The former type is commonly found in many forms of racing cars, older heavy-duty trucks, and some agricultural equipment.

Manual transmissions are the most common type outside North America and Australia. They are cheaper, lighter, usually give better performance, and fuel efficiency (although automatic transmissions with torque convertor lockup and advanced electronic controls can provide similar results). It is customary for new drivers to learn, and be tested, on a car with a manual gear change. In Malaysia, Denmark and Poland all cars used for testing (and because of that, virtually all those used for instruction as well) have a manual transmission. In Japan, the Philippines, Germany, Italy, Israel, the Netherlands, Belgium, New Zealand, Austria, Bulgaria, the UK, Ireland, Sweden, Estonia, France, Spain, Switzerland, the Australian states of Victoria, Western Australia and Queensland, Finland and Lithuania, a test pass using an automatic car does not entitle the driver to use a manual car on the public road; a test with a manual car is required. Manual transmissions are much more common than automatic transmissions in Asia, Africa, South America and Europe.

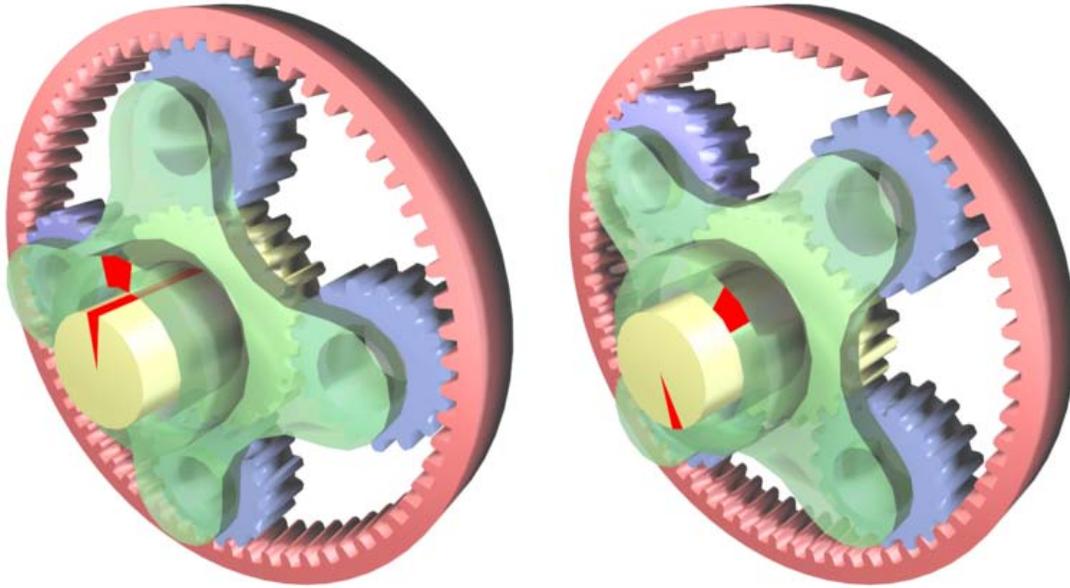
Many manual transmissions include both synchronized and unsynchronized gearing; it is not uncommon for the first/reverse gear to lack synchros. Those gears are meant to be shifted into only when the vehicle is stopped.

Some manual transmissions have an extremely low ratio for first gear, which is referred to as a "creeper gear" or "granny gear". Such gears are usually not synchronized. This feature is common on pickup trucks tailored to trailer-towing, farming, or construction-site work. During normal on-road use, the truck is usually driven without using the creeper gear at all, and second gear is used from a standing start.

Non-synchronous

There are commercial applications engineered with designs taking into account that the gear shifting will be done by an experienced operator. They are a manual transmission, but are known as non-synchronized transmissions. Dependent on country of operation, many local, regional, and national laws govern the operation of these types of vehicles. This class may include commercial, military, agricultural, or engineering vehicles. Some of these may use combinations of types for multi-purpose functions. An example would be a PTO, or *power-take-off* gear. The non-synchronous transmission type requires an understanding of gear range, torque, engine power, and multi-functional clutch and shifter functions.

Automatic



Epicyclic gearing or planetary gearing as used in an automatic transmission.

Most modern North American and Australian and many larger, high specification European and Japanese cars have an automatic transmission that will select an appropriate gear ratio without any operator intervention. They primarily use hydraulics to select gears, depending on pressure exerted by fluid within the transmission assembly. Rather than using a clutch to engage the transmission, a fluid flywheel, or torque converter is placed in between the engine and transmission. It is possible for the driver to control the number of gears in use or select reverse, though precise control of which gear is in use may or may not be possible.

Automatic transmissions are easy to use. However, in the past, automatic transmissions of this type have had a number of problems; they were complex and expensive, sometimes had reliability problems (which sometimes caused more expenses in repair), have often been less fuel-efficient than their manual counterparts (due to "slippage" in the torque converter), and their shift time was slower than a manual making them uncompetitive for racing. With the advancement of modern automatic transmissions this has changed.

Attempts to improve the fuel efficiency of automatic transmissions include the use of torque converters which lock up beyond a certain speed, or in the higher gear ratios, eliminating power loss, and overdrive gears which automatically actuate above certain speeds; in older transmissions both technologies could sometimes become intrusive, when conditions are such that they repeatedly cut in and out as speed and such load factors as grade or wind vary slightly. Current computerized transmissions possess very complex programming to both maximize fuel efficiency and eliminate any intrusiveness.

For certain applications, the slippage inherent in automatic transmissions can be advantageous; for instance, in drag racing, the automatic transmission allows the car to be stopped with the engine at a high rpm (the "stall speed") to allow for a very quick launch when the brakes are released; in fact, a common modification is to increase the stall speed of the transmission. This is even more advantageous for turbocharged engines, where the turbocharger needs to be kept spinning at high rpm by a large flow of exhaust in order to keep the boost pressure up and eliminate the turbo lag that occurs when the engine is idling and the throttle is suddenly opened.

Semi-automatic

The creation of computer control also allowed for a sort of cross-breed transmission where the car handles manipulation of the clutch automatically, but the driver can still select the gear manually if desired. This is sometimes called a "clutchless manual," or "automated manual" transmission. Many of these transmissions allow the driver to give full control to the computer. They are generally designed using manual transmission "internals", and when used in passenger cars, have synchromesh operated helical constant mesh gear sets.

Specific type of this transmission includes: Easytronic, and Geartronic.

A "dual-clutch" transmission uses two sets of internals which are alternately used, each with its own clutch, so that only the clutches are used during the actual "gearchange".

Specific type of this transmission includes: Direct-Shift Gearbox.

There are also sequential transmissions which use the rotation of a drum to switch gears.

Bicycle gearing



Shimano XT rear derailleur on a mountain bike

Bicycles usually have a system for selecting different gear ratios. There are two main types: derailleur gears and hub gears. The derailleur type is the most common, and the most visible, using sprocket gears. Typically there are several gears available on the rear sprocket assembly, attached to the rear wheel. A few more sprockets are usually added to the front assembly as well. Multiplying the number of sprocket gears in front by the number to the rear gives the number of gear ratios, often called "speeds".

Hub gears use epicyclic gearing and are enclosed within the axle of the rear wheel. Because of the small space, they typically offer fewer different speeds, although at least

one has reached 14 gear ratios and Fallbrook Technologies manufactures a transmission with technically infinite ratios.

Causes for failure of bicycle gearing include: worn teeth, damage caused by a faulty chain, damage due to thermal expansion, broken teeth due to excessive pedaling force, interference by foreign objects, and loss of lubrication due to negligence.

Uncommon types

Dual clutch transmission

This arrangement is also sometimes known as a direct shift gearbox or powershift gearbox. It seeks to combine the advantages of a conventional manual shift with the qualities of a modern automatic transmission by providing different clutches for odd and even speed selector gears. When changing gear, the engine torque is transferred from one gear to the other continuously, so providing gentle, smooth gear changes without either losing power or jerking the vehicle. Gear selection may be manual, automatic (depending on throttle/speed sensors), or a 'sports' version combining both options.

Continuously variable

The Continuously Variable Transmission (CVT) is a transmission in which the ratio of the rotational speeds of two shafts, as the input shaft and output shaft of a vehicle or other machine, can be varied continuously within a given range, providing an infinite number of possible ratios.

The continuously variable transmission (CVT) should not be confused with the Infinitely Variable Transmission (IVT).

The other mechanical transmissions described above only allow a few different gear ratios to be selected, but this type of transmission essentially has an infinite number of ratios available within a finite range. The continuously variable transmission allows the relationship between the speed of the engine and the speed of the wheels to be selected within a continuous range. This can provide even better fuel economy if the engine is constantly running at a single speed. The transmission is in theory capable of a better user experience, without the rise and fall in speed of an engine, and the jerk felt when poorly changing gears.

Infinitely variable

The IVT is a specific type of CVT that has an infinite range of input/output ratios in addition to its infinite number of possible ratios; this qualification for the IVT implies that its range of ratios includes a zero output/input ratio that can be continuously approached from a defined 'higher' ratio. A zero output implies an infinite input, which can be continuously approached from a given finite input value with an IVT. [Note: remember that so-called 'low' gears are a reference to low ratios of output/input, which

have high input/output ratios that are taken to the extreme with IVTs, resulting in a 'neutral', or non-driving 'low' gear limit.]

Most (if not all) IVTs result from the combination of a CVT with an epicyclic gear system (which is also known as a planetary gear system) that facilitates the subtraction of one speed from another speed within the set of input and planetary gear rotations. This subtraction only needs to result in a continuous range of values that includes a zero output; the maximum output/input ratio can be arbitrarily chosen from infinite practical possibilities through selection of extraneous input or output gear, pulley or sprocket sizes without affecting the zero output or the continuity of the whole system. Importantly, the IVT is distinguished as being 'infinite' in its ratio of high gear to low gear within its range; high gear is infinite times higher than low gear. The IVT is always engaged, even during its zero output adjustment.

The term 'infinitely variable transmission' does not imply reverse direction, disengagement, automatic operation, or any other quality except ratio selectability within a continuous range of input/output ratios from a defined minimum to an undefined, 'infinite' maximum. This means continuous range from a defined output/input to zero output/input ratio.

Electric variable

The Electric Variable Transmission (EVT) is a transmission that achieves CVT action and in addition can use separate power inputs to produce one output. An EVT is usually designed around an epicyclic differential gear system (also known as a planetary gear system). The epicyclic gear acts as a differential, performing a "power-split" function; a portion of the mechanical power is carried directly through the gear set (the "mechanical path"). The rest of the power is converted to and from electrical energy by electric motor-generators (the "electrical path"). Hence, the EVT is a class of Power Split Transmission (PST).

Many EVTs are linked to batteries or other electrical energy storage devices. This enables them to store or draw electrical power for better operation under various conditions.

The pair of motor/generators forms an Electric Transmission in its own right, but at a lower capacity, than the EVT it is contained within. Generally the Electric Transmission capacity within the EVT is a quarter to a half of the capacity of the EVT. An EVT is often preferable to a pure electrical transmission because the mechanical transmission is cheaper, more compact, and more efficient than the electrical path.

The EVT linked to a battery is the essential method for transmitting power in some hybrid vehicles, enabling an Internal Combustion Engine (ICE) to be used in conjunction with motor/generators for vehicle propulsion. Vehicle speed is controlled primarily by adjusting the amount of power flowing through the electrical as opposed to the mechanical path. The EVT may be used to generate electrical power for storage in a battery, especially through 'regenerative braking' during deceleration. Various

configurations of power generation, usage and balance can be implemented with an EVT, enabling great flexibility in propelling hybrid vehicles.

The Toyota single mode hybrid and General Motor 2 Mode hybrid are production systems that use EVTs. The Toyota system is in the Prius, Highlander, and Lexus RX400h and GS450h models. The GM system is used in the Allison Bus hybrid powertrains and the Tahoe and Yukon models. The Toyota system uses one power-split epicyclic differential gearing system over all driving conditions and is sized with an electrical path rated at approximately half the capacity of the EVT. The GM system uses two different EVT ranges: one designed for lower speeds with greater mechanical advantage, and one designed for higher speeds. The electrical path is rated at approximately a quarter of the capacity of the EVT. Other arrangements are possible and applications of EVTs are growing rapidly in number and variety.

EVTs are capable of continuously modulating output/input speed ratios like mechanical CVTs, but offer the distinct difference and benefit of being able to also apportion power from two different sources to one output.

Hydrostatic

Hydrostatic transmissions transmit all power hydraulically, using the components of hydraulic machinery. Hydrostatic transmissions do not make use of the hydrodynamic forces of the fluid flow. There is no solid coupling of the input and output. The transmission input drive is a central hydraulic pump and final drive unit(s) is/are a hydraulic motor, or hydraulic cylinder. Both components can be placed physically far apart on the machine, being connected only by flexible hoses. Hydrostatic drive systems are used on excavators, lawn tractors, forklifts, winch drive systems, heavy lift equipment, agricultural machinery, etc. An arrangement for motor-vehicle transmission was probably used on the Ferguson *F-1* P99 racing car in about 1961.

The Human Friendly Transmission of the Honda DN-01 is hydrostatic.

Hydrodynamic

If the hydraulic pump and/or hydraulic motor make use of the hydrodynamic effects of the fluid flow, i.e. pressure due to a change in the fluid's momentum as it flows through vanes in a turbine. The pump and motor usually consist of rotating vanes without seals and are typically placed in close proximity. The transmission ratio can be made to vary by means of additional rotating vanes, an effect similar to varying the pitch of an airplane propeller.

The torque converter in most automotive automatic transmissions is, in itself, a hydrodynamic transmission.

It was possible to drive the Dynaflo transmission without shifting the mechanical gears.

Hydrodynamic transmissions are used in many passenger rail vehicles. In this application the advantage of smooth power delivery may outweigh the reduced efficiency caused by turbulence energy losses in the fluid.

Electric

Electric transmissions convert the mechanical power of the engine(s) to electricity with electric generators and convert it back to mechanical power with electric motors. Electrical or electronic adjustable-speed drive control systems are used to control the speed and torque of the motors. If the generators are driven by turbines, such arrangements are called turbo-electric. Likewise installations powered by diesel-engines are called diesel-electric. Diesel-electric arrangements are used on many railway locomotives, ships and large mining trucks.

Virtual transmission

Virtual Transmission allows for the same traction motor to be both a low-speed high torque and high-speed electric motor, using the winding/software that runs on the new electric motors. This virtual transmission will require less complex engineering, and less weight. The alternator and starter for the Chevrolet Volt can be combined into a single armature, smaller and lighter than each alternator and starter individually.

Chapter 12

Gear Ratio



Gears on a piece of farm equipment, total (3 gears) gear ratio $42/13 = 3.23$

The **gear ratio** is the relationship between the numbers of teeth on two gears that are meshed or two sprockets connected with a common roller chain, or the circumferences of two pulleys connected with a drive belt.

General description

The input or driver gear in a gear train is the gear directly connected to the motor or other power source. Thus the driver is the gear that transmits power to the other gears in the gear train. In a simple 2-gear system, the second gear (the gear which is *turned by* the driver) is called the output or driven gear. In a gear train consisting of more than 2 gears, the final gear (the gear connected to a wheel axle or other rotating mechanical component) is the output gear.

gear ratio (gr) = (number of teeth on output or driven gear)/(number of teeth on input or driver gear)

If we assume that in the photo the smallest gear is connected to the motor, then it is the driver gear. The somewhat larger gear on the upper left is called an idler gear -- it is not connected directly to either the motor or the output shaft and serves only to transmit power between the input and output gears. There is a third gear in the upper-right corner of the photo. If we assume that gear is connected to the machine's output shaft, it is the output or driven gear.

The idler gear in this particular gear train has 21 teeth and the input gear has 13. *Considering for the moment only those two gears*, we can regard the idler as the driven gear. Therefore, the gear ratio is driven/driver = $21/13 = \sim 1.62$ or 1.62:1.

The ratio means that the driver gear must make 1.62 revolutions to turn the driven gear 1 revolution. It also means that for every one revolution of the driver, the driven gear has made $1/1.62$, or 0.62, revolutions. In practical terms, the larger gear turns more slowly.

Now suppose the third gear in the picture has 42 teeth. The gear ratio between the idler and third gear is thus $42/21$, or 2:1, and hence the final gear ratio is $1.62 \times 2 = \sim 3.23$. For every 3.23 revolutions of the smallest gear, the largest gear turns one revolution, or for every one revolution of the smallest gear, the largest gear turns 0.31 ($1/3.23$) revolution, a total reduction of about 1:3.23 (Gear Reduction Ratio (GRR) = $1/\text{Gear Ratio (GR)}$).

Since the intermediate (idler) gear contacts directly both the smaller and the larger gear it can be removed from the calculation, also giving a ratio of $42/13 = \sim 3.23$.

Since the number of teeth is also proportional to the circumference of the gear wheel (the bigger the wheel the more teeth it has) the gear ratio can also be expressed as the relationship between the pitch circles of both wheels (where d is the pitch diameter of the input wheel and D is the pitch diameter of the output wheel):

$$gr = \frac{\pi D}{\pi d} = \frac{D}{d}$$

Pitch circles have diameters that would give the same gear ratio, but with cylindrical surfaces that do not slip.

Since the diameter is equal to twice the radius;

$$gr = \frac{D}{d} = \frac{2R}{2r} = \frac{R}{r}$$

as well.

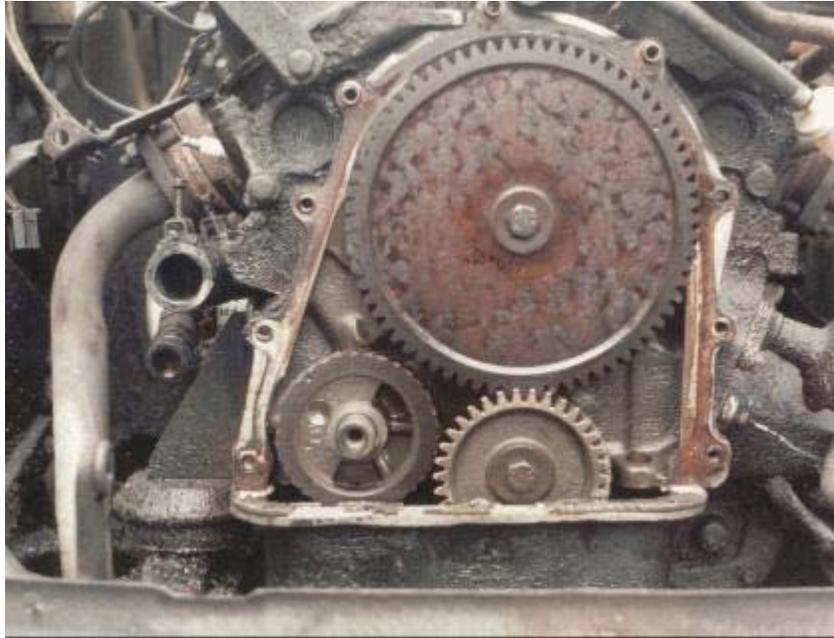
$$v_d = v_D \rightarrow \omega_d r = \omega_D R \rightarrow \frac{R}{r} = \frac{\omega_d}{\omega_D}$$

and so

$$gr = \frac{\omega_d}{\omega_D}$$

In other words, the gear ratio is proportional to ratio of the pitch circles and inversely proportional to the ratio of gear speeds.

Belts can have teeth in them also and be coupled to gear-like pulleys. Special gears called sprockets can be coupled together with chains, as on bicycles and some motorcycles. Again, exact accounting of teeth and revolutions can be applied with these machines.



Valve timing gears on a Ford Taunus V4 engine — the small gear is on the crankshaft, the larger gear is on the camshaft. The crankshaft gear has 34 teeth, the camshaft gear has 68 teeth and runs at half the crankshaft RPM.
(The small gear in the lower left is on the balance shaft.)

A belt with teeth, called the timing belt, is used in some internal combustion engines to exactly synchronize the movement of the camshaft with that of the crankshaft, so that the valves open and close at the top of each cylinder at exactly the right time relative to the movement of each piston. From the time the car is driven off the lot, to the time the belt needs replacing thousands of kilometers later, it synchronizes the two shafts exactly. A chain, called a timing chain, is used on some automobiles for this purpose, while in others, the camshaft and crankshaft are coupled directly together through meshed gears. But whichever form of drive is employed, on four-stroke engines the crankshaft/camshaft gear ratio is always 2:1, which means that for every two revolutions of the crankshaft the camshaft will rotate through one revolution. (In case of 4 stroke engines the valve cycle is repeated after every two rotations of the flywheel.)

Automobile drivetrains generally have two or more areas where gearing is used: one in the transmission, which contains a number of different sets of gearing that can be changed to allow a wide range of vehicle speeds, and another at the differential, which contains one additional set of gearing that provides further speed reduction at the wheels. As well, the differential contains further gearing that splits torque equally between the two wheels while permitting them to have different speeds when traveling a curved path. The components might be separate and connected by a driveshaft, or they might be combined into one unit called a transaxle.

A 2004 Chevrolet Corvette C5 Z06 with a six-speed manual transmission has the following gear ratios in the transmission:

Gear	Ratio
1st gear	2.97:1
2nd gear	2.07:1
3rd gear	1.43:1
4th gear	1.00:1
5th gear	0.84:1
6th gear	0.56:1
reverse	3.38:1

In 1st gear, the engine makes 2.97 revolutions for every revolution of the transmission's output. In 4th gear, the gear ratio of 1:1 means that the engine and the transmission's output are moving at the same speed. 5th and 6th gears are known as overdrive gears, in which the output of the transmission is revolving faster than the engine.

The Corvette above has a differential ratio of 3.42:1. The ratio means that for every 3.42 revolutions of the transmission's output, the wheels make one revolution. The differential ratio multiplies with the transmission ratio, so in 1st gear, the engine makes 10.16 revolutions for every revolution of the wheels.

The car's tires can almost be thought of as a third type of gearing. The example Corvette Z06 is equipped with 295/35-18 tires, which have a circumference of 82.1 inches. This means that for every complete revolution of the wheel, the car travels 82.1 inches. If the Corvette had larger tires, it would travel farther with each revolution of the wheel, which would be like a higher gear. If the car had smaller tires, it would be like a lower gear.

With the gear ratios of the transmission and differential, and the size of the tires, it becomes possible to calculate the speed of the car for a particular gear at a particular engine RPM.

For example, it is possible to determine the distance the car will travel for one revolution of the engine by dividing the circumference of the tire by the combined gear ratio of the transmission and differential.

$$d = \frac{c_t}{gr_t \times gr_d}$$

It is possible to determine a car's speed from the engine speed by multiplying the circumference of the tire by the engine speed and dividing by the combined gear ratio.

$$v_c = \frac{c_t \times v_e}{gr_t \times gr_d}$$

Gear	Distance per engine revolution	Speed per 1000 RPM
1st gear	8.1 in (210 mm)	7.7 mph (12.4 km/h)
2nd gear	11.6 in (290 mm)	11.0 mph (17.7 km/h)
3rd gear	16.8 in (430 mm)	15.9 mph (25.6 km/h)
4th gear	24.0 in (610 mm)	22.7 mph (36.5 km/h)
5th gear	28.6 in (730 mm)	27.1 mph (43.6 km/h)
6th gear	42.9 in (1,090 mm)	40.6 mph (65.3 km/h)

Wide-ratio vs. close-ratio transmission

A close-ratio transmission is a transmission in which there is a relatively little difference between the gear ratios of the gears. For example, a transmission with an engine shaft to drive shaft ratio of 4:1 in first gear and 2:1 in second gear would be considered wide-ratio when compared to another transmission with a ratio of 4:1 in first and 3:1 in second. This is because, for the wide-ratio first gear = $4/1 = 4$, second gear = $2/1 = 2$, so the transmission gear ratio = $4/2 = 2$ (or 200%). For the close-ratio first gear = $4/1 = 4$, second gear = $3/1 = 3$ so the transmission gear ratio = $4/3 = 1.33$ (or 133%), because 133% is less than 200%, the transmission with the 133% ratio between gears is considered close-ratio. However, not all transmissions start out with the same ratio in 1st gear or end with the same ratio in 5th gear, which makes comparing wide vs. close transmission more difficult.

Close-ratio transmissions are generally offered in sports cars, in which the engine is tuned for maximum power in a narrow range of operating speeds and the driver can be expected to enjoy shifting often to keep the engine in its power band.

Factory 4-speed or 5-speed transmission ratios are good compromises for mixed street and moderate performance use, and are "staged" or "progressive", in that the engine speed loss on shifting from 1st to 2nd is higher than the loss on shifting from 2nd to 3rd and so on. The purpose is to keep the engine in its torque range at higher vehicle speed, where wind resistance requires more power for acceleration. Wider gaps between ratios will allow a "stronger" (higher numerically, e.g. 2.90:1 instead of 2.50:1) 1st gear for better manners in traffic, but increase the RPM lost on shifting. Narrowing the gaps will increase acceleration at speed, and potentially improve top speed under certain conditions, but acceleration from stopped and operation in traffic will suffer.

The 1st gear ratio for most 4-speed transmissions is about 2.50:1, and 4th is almost always 1.00:1. The ratios of 2nd and 3rd are placed in between these two, and are discretionary to best serve the weight, intended use, speed, engine tune, and other features of the vehicle.

"Range" is the torque multiplication difference between 1st and 4th gears; wider-ratio gear-sets have more, typically between 2.8 and 3.2. This is the single most important determinant of low-speed acceleration from stopped.

"Progression" is the next factor. This is the reduction or decay in the percentage drop in engine speed in the next gear (e.g. after shifting from 1st to 2nd). Most transmissions have some degree of progression in that the RPM drop on the 1-2 shift is larger than the RPM drop on the 2-3 shift, which is in turn larger than the RPM drop on the 3-4 shift. The progression may not be linear (continuously reduced) or done in proportionate stages for various reasons, including a special need for a gear to reach a specific speed or RPM for passing, racing and so on, or simply economic necessity that the parts were available.

The two factors are not mutually exclusive, but each limits the number of options for the other. A wide range, which gives a strong torque multiplication in 1st gear for excellent manners in low-speed traffic (especially with a smaller motor, heavy chassis or numerically low axle ratio such as 2.50) mean that the progression percentages must all be high. The amount of engine speed (and therefore power) that must be lost on each up-shift is higher than would be the case in a transmission with less range (but less power in 1st gear). A numerically low 1st gear (2.00, &c.) reduces available torque in 1st gear, but allows more choices of progression.

There is no choice of ratios that gives the "best" performance at all speeds, nor is there a choice of final drive (axle) ratio that gives the "best" performance at all speeds. It simply does not exist, all ratios are compromises, and not necessarily better than the original ratios for most use.

The advantage of a close ratio gear-set lies in the fact that the RPM loss at very high speed is reduced, allowing extra power to accelerate above 100 mph. However, of necessity, the torque multiplier in the lower gears is reduced by the same proportion, and performance at low speeds is much worse. Even for road racing, the closest possible ratio is not always the best choice since many races begin with a grid start (favoring slightly wider ratios with high progression, where 1st gear acceleration is very important) and some with a flying start (favoring close ratios, where 1st gear acceleration is less important).

In general, engines with smaller displacement, very long duration cams, ported heads, large carburetors and so on don't pull well from low rpm, and when the 3-4 shift will benefit more from close ratios in the upper gears, and even more so as the maximum speed at a specific course increases. If the shift takes place at a speed where air resistance is high (70+ mph), closer ratios are better. If your engine has been specifically designed for a tuned RPM torque peak (or if that is how the engine behaves), the transmission ratios must be chosen to ensure that after each shift during a lap the engine speed recovers to a point above this peak at that specific track. From the negative viewpoint, the ratios must be arranged to avoid dropping the engine into a "hole" on an up shift, where power falls off disproportionately.

If the widest ratio change gives a 25% loss, the shift RPM is 7,000 RPM, and there is a torque increase at 5,000 RPM you're safe: $7,000 - 25\% = 5,250$, the engine will be in this desirable range on acceleration.

If the widest ratio change is 30%, shift at 7,000, and torque at 5,500: $7,000 - 30\% = 4,900$, far below the power range and the acceleration (and perhaps the jetting) will be weak until you reach 5,500. You will definitely benefit from a closer gear set, or at least re-arranging the progression to reduce the 30% drop to a better number. Depending on the bike and the track, adding to the drop in the previous gear pair (i.e., problem with the 2-3 shift: add some drop to the 1-2 not the 3-4) is the 1st choice but results will vary.

Individual race tracks with combination of maximum speed and corner speed will require different intermediate (2nd & 3rd) gears to allow downshifting for a specific gear to enter a turn, or to use only one gear during a turn to avoid traction loss. The key to analysis here is whether your favorite track has a spot where the engine is "flat" after shifting at an awkward moment in a turn, but better as it speeds up.

Idler gear

In a sequence of gears chained together, the ratio depends only on the number of teeth on the first and last gear. The intermediate gears, regardless of their size, do not alter the overall gear ratio of the chain. However, the addition of each intermediate gear reverses the direction of rotation of the final gear.

An intermediate gear which does not drive a shaft to perform any work is called an idler gear. Sometimes, a single idler gear is used to reverse the direction, in which case it may be referred to as a *reverse idler*. For instance, the typical automobile manual transmission engages reverse gear by means of inserting a reverse idler between two gears.

Idler gears can also transmit rotation among distant shafts in situations where it would be impractical to simply make the distant gears larger to bring them together. Not only do larger gears occupy more space, the mass and rotational inertia (moment of inertia) of a gear is proportional to the square of its radius. Instead of idler gears, a toothed belt or chain can be used to transmit torque over distance.