

Gear Systems & Mechanical Engineering



Refugio Negrón

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Chapter 1

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 sprocket (high)	40 tooth front inner 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.

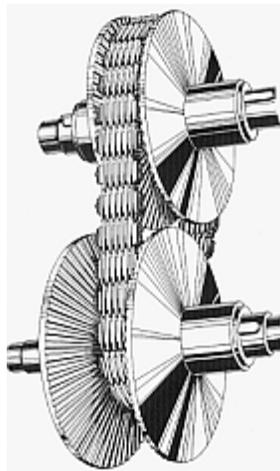
For gear ratios they also need to know the length of the pedal cranks in millimetres (crank lengths are normally some multiple of 2.5 mm). If the bicycle has an enclosed gear system (hub or bottom bracket), then details of these gears are also needed (make and model is enough for some calculators).

Chapter 2

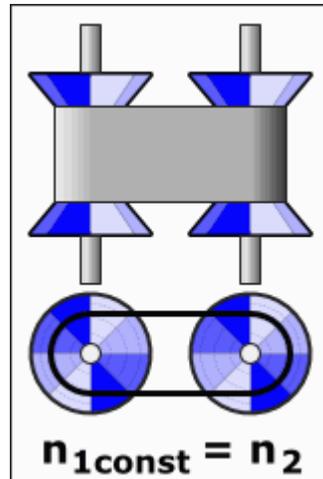
Continuously Variable Transmission

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.

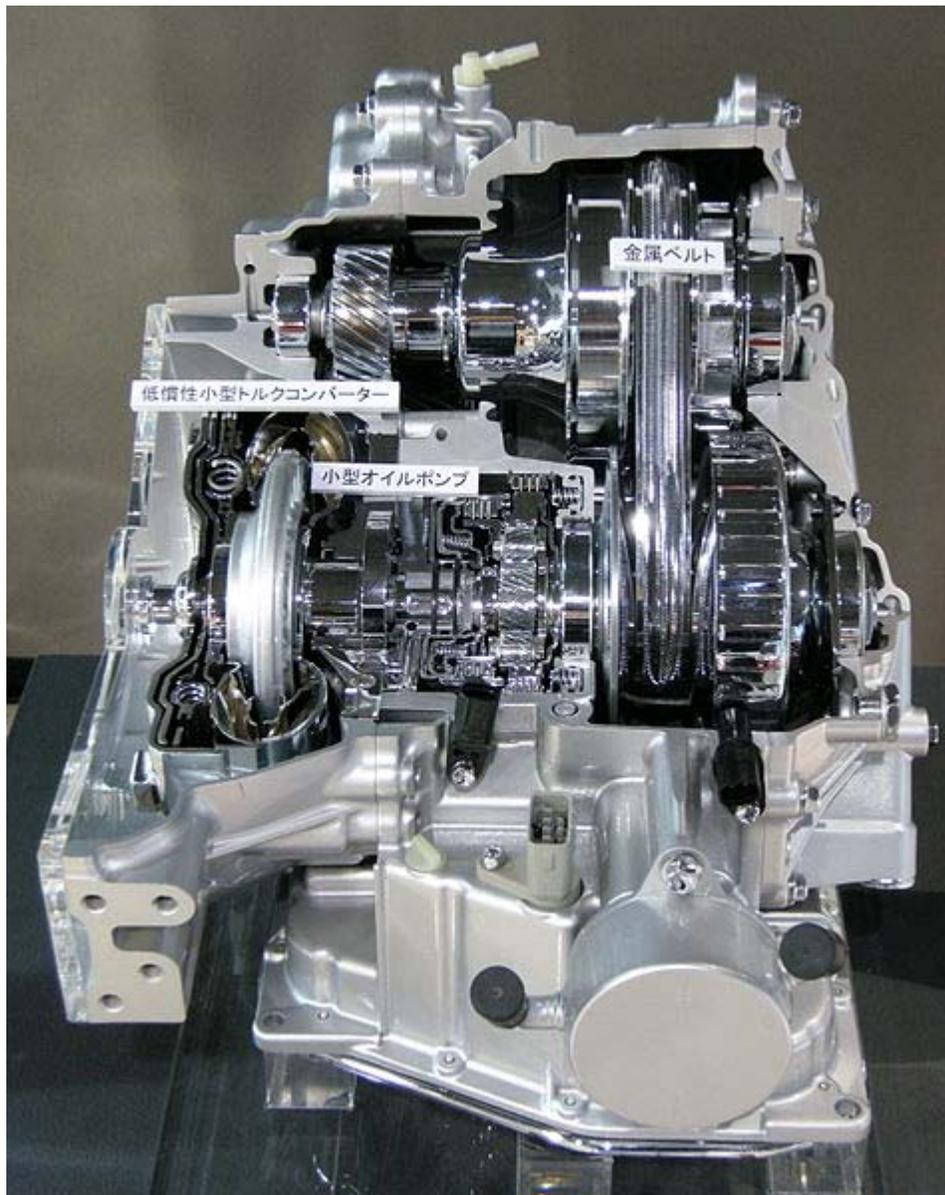
Some combine harvesters have CVTs. The CVT allows the forward speed of the combine to be adjusted independently of the engine speed. This allows the operator to slow or accelerate as needed to accommodate variations in thickness of the crop.

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.

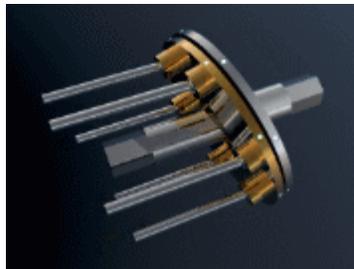
Ratcheting CVT

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

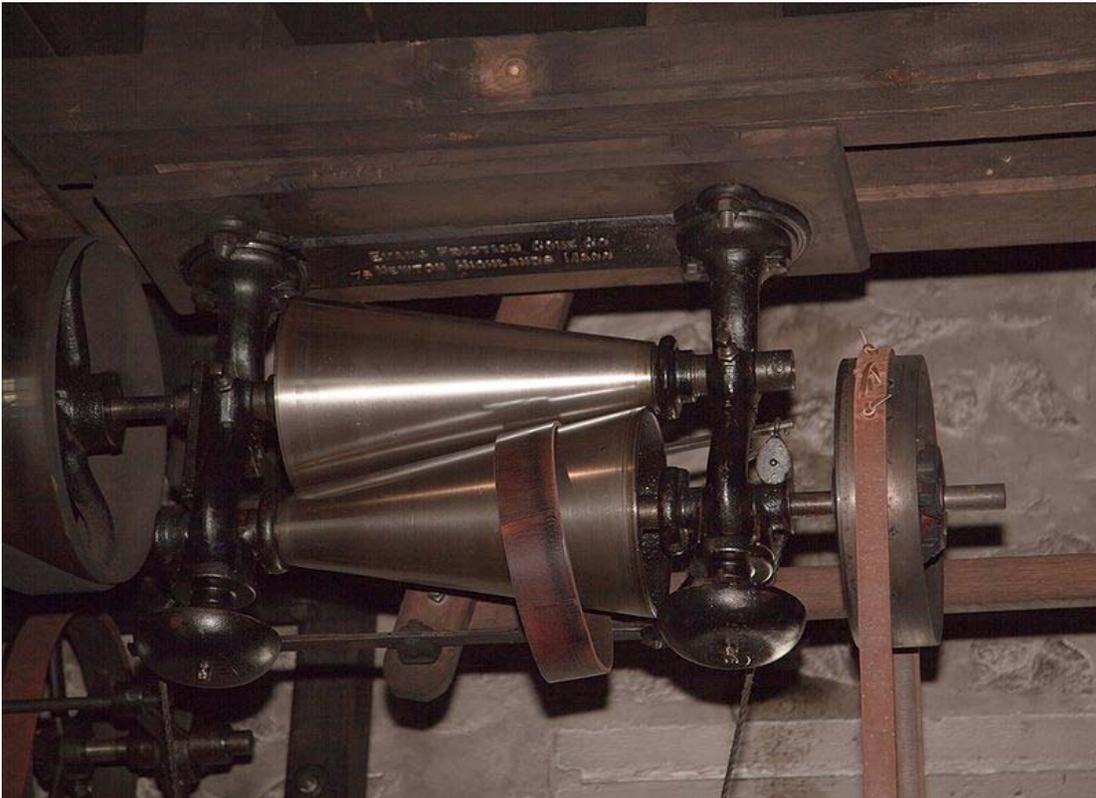
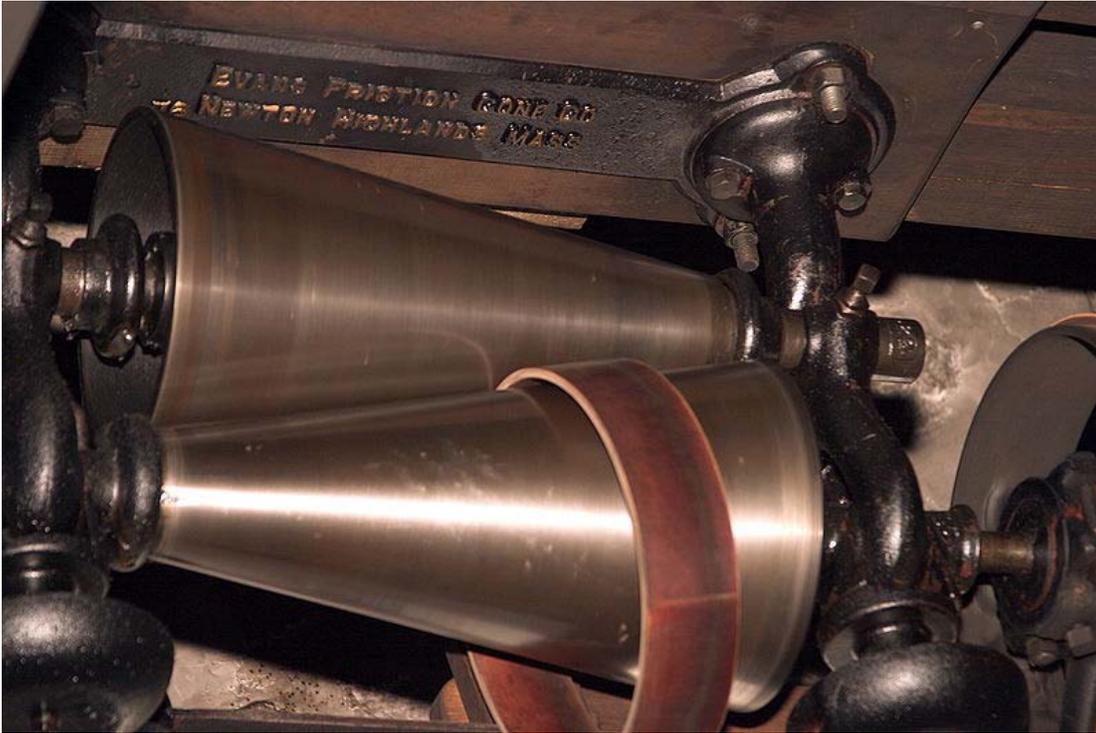
The teeth of the variator pulley of an iCVT are formed by pins that extend from one pulley half to the other pulley half and slide in the grooves of the pulley halves of the variator pulley. Here torque from the chain is transferred to the pins and then from the pins to the pulley halves. Since the pins 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'.

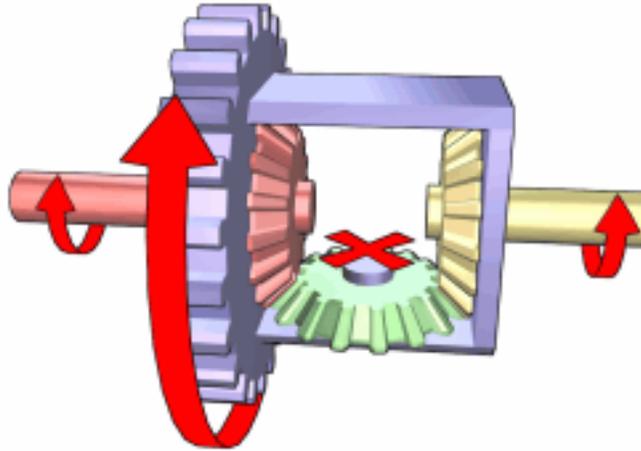
Subaru offers CVT on the 2010 Legacy and 2010 Outback (Lineartronic).

Chapter 3

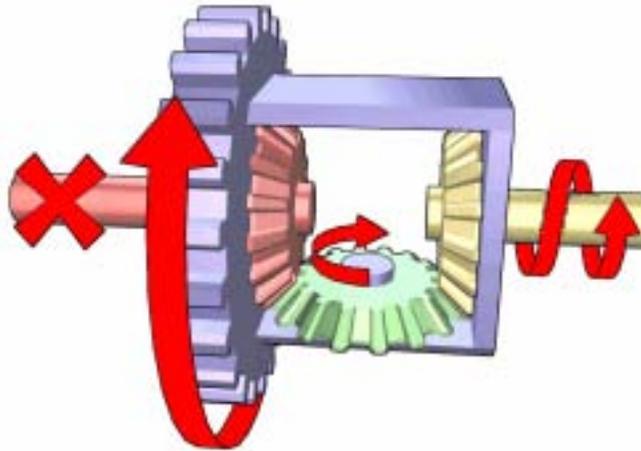
Differential (Mechanical Device)



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).

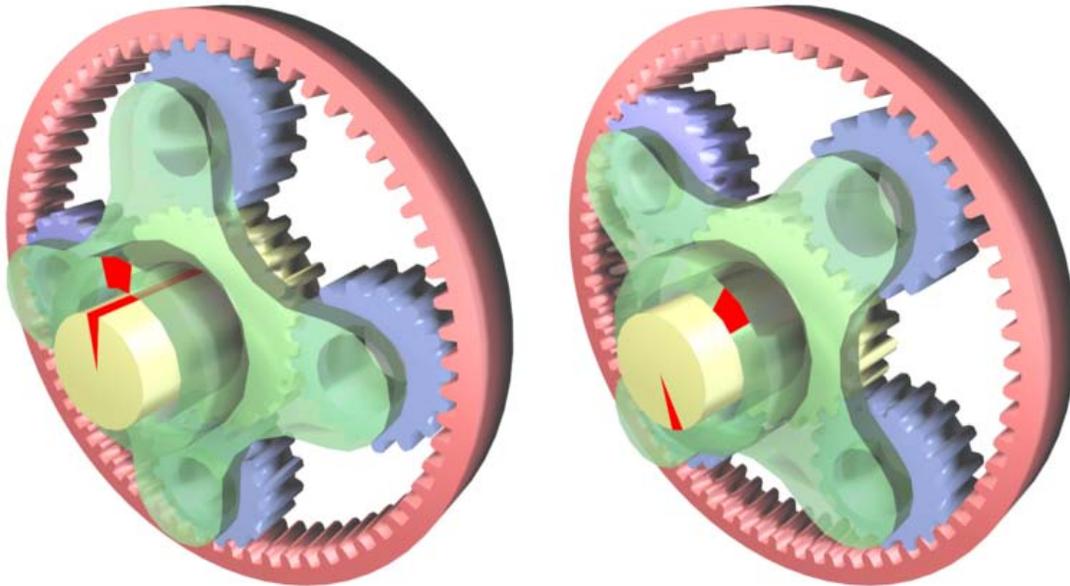
- A Spool is just what it sounds like. It may replace the spider gears within the differential carrier, or the entire carrier. A spool locks both axle shafts together 100% for maximum traction. This is typically only used in drag racing applications, where the vehicle is to be driven in a straight line 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 4

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.

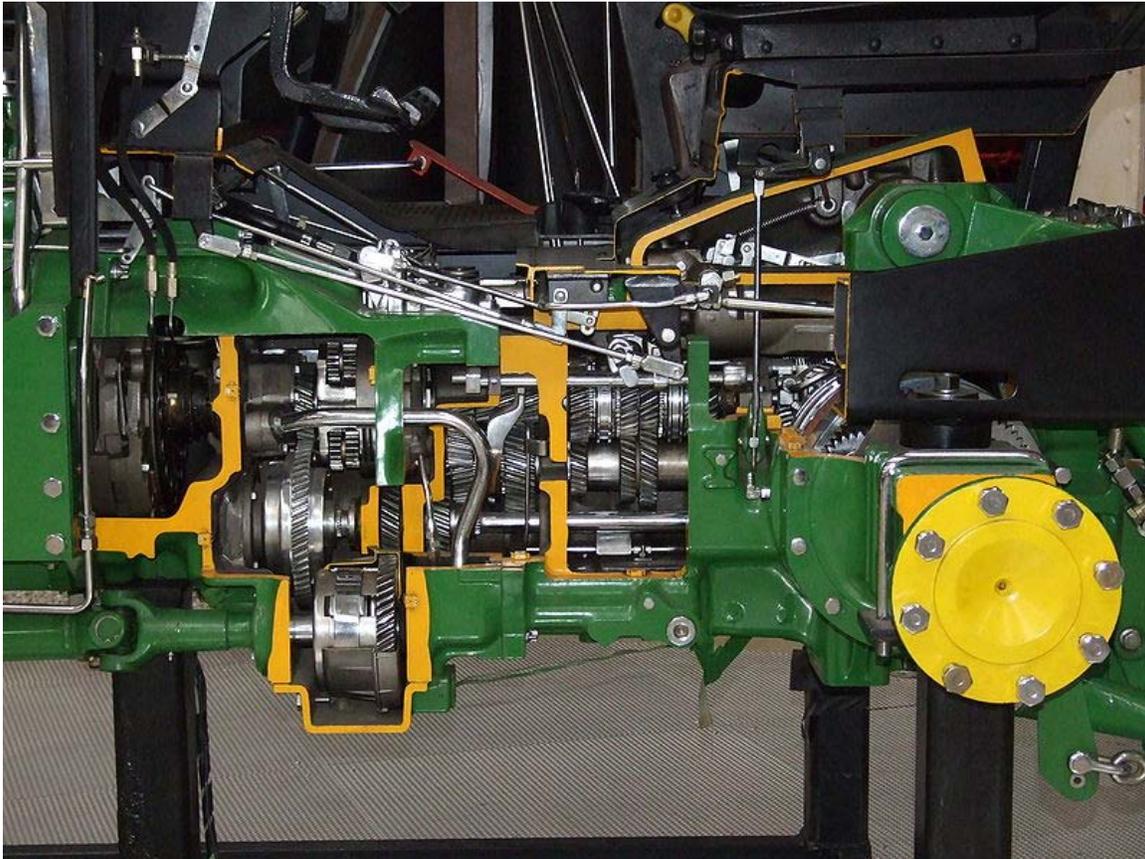
Simple

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.

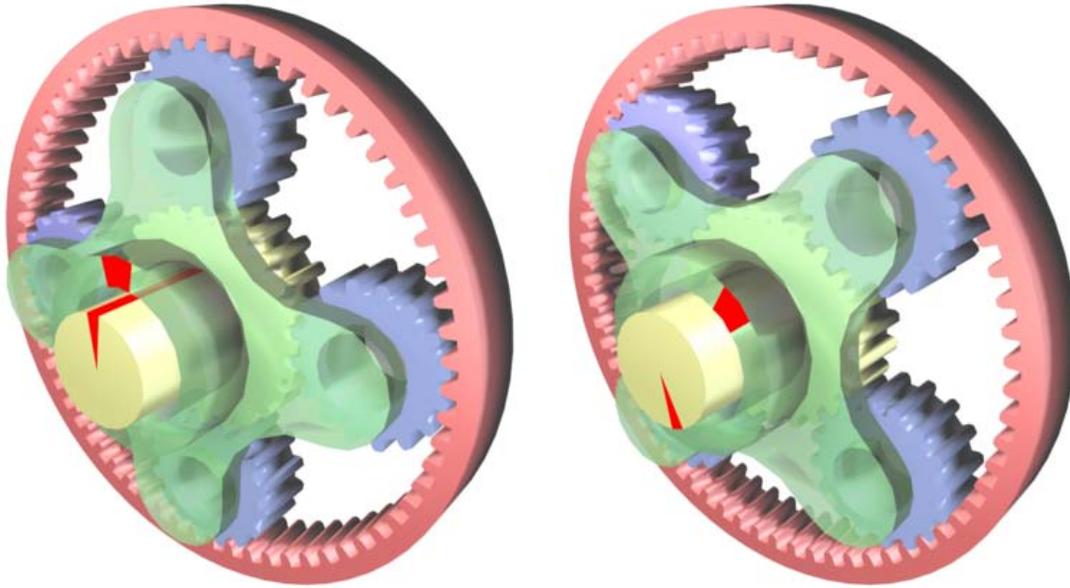
Many manual transmissions include both synchronized and unsynchronized gearing; it is not uncommon for the first/reverse gear to lack synchros. Those gears are meant to be shifted into only when the vehicle is stopped.

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 EVT's 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 5

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.

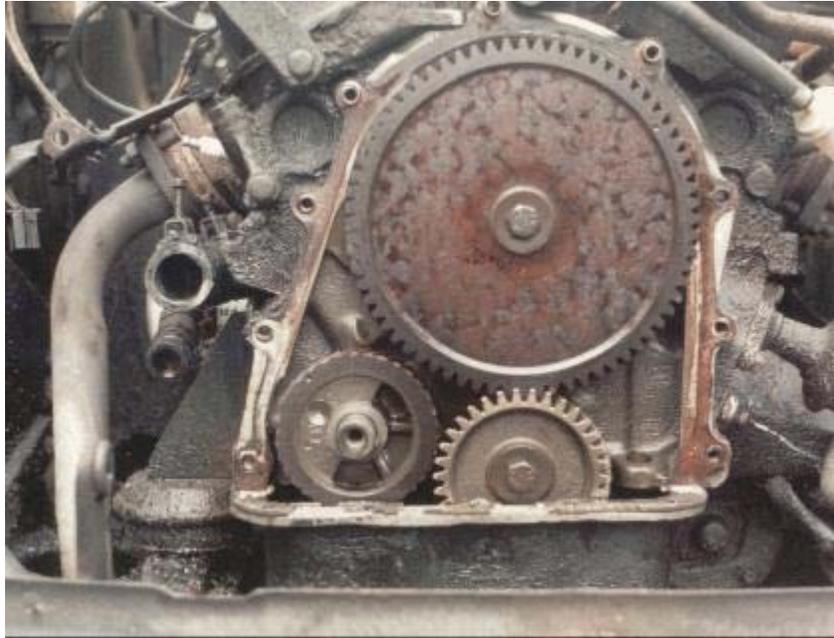
$$v_d = v_D \rightarrow \omega_d r = \omega_D R \rightarrow \frac{R}{r} = \frac{\omega_d}{\omega_D}$$

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

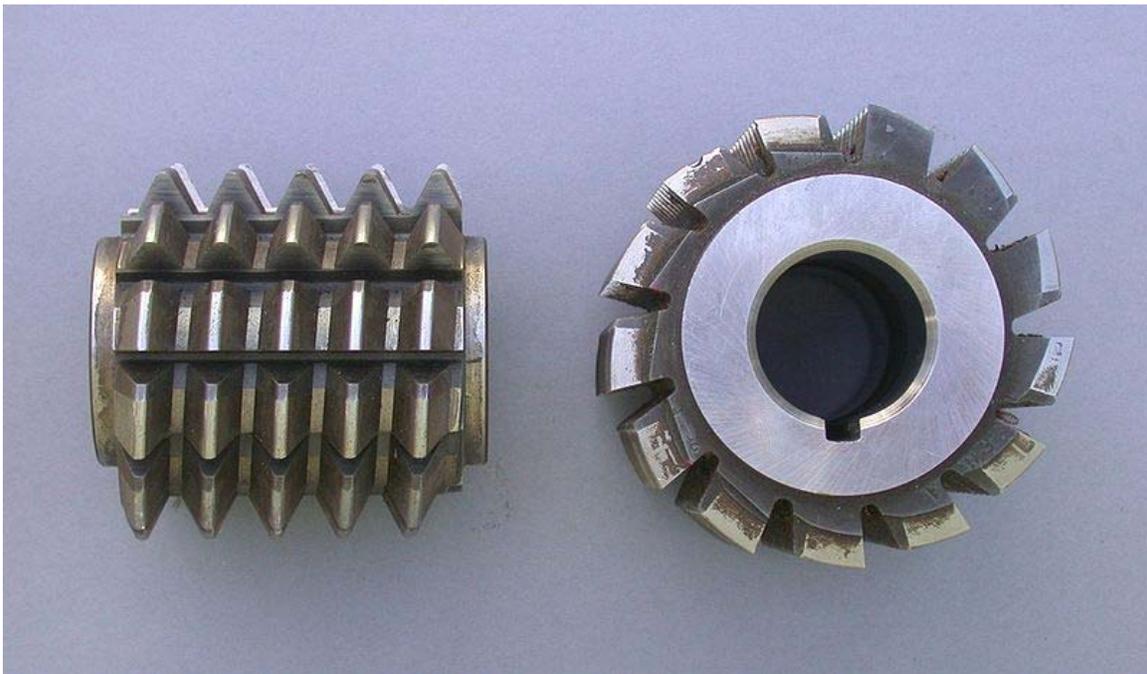
In a sequence of gears chained together, the ratio depends only on the number of teeth on the first and last gear. The intermediate gears, regardless of their size, do not alter the overall gear ratio of the chain. However, the addition of each intermediate gear reverses the direction of rotation of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

Chapter 6

Hobbing



A hob — the cutter used for hobbing.

Hobbing is a machining process for making gears, splines, and sprockets on a *hobbing machine*, which is a special type of milling machine. The teeth or splines are progressively cut into the workpiece by a series of cuts made by a cutting tool called a *hob*. Compared to other gear forming processes it is relatively inexpensive but still quite accurate, thus it is used for a broad range of parts and quantities.

It is the most widely used gear cutting process for creating spur and helical gears and more gears are cut by hobbing than any other process since it is relatively quick and inexpensive.

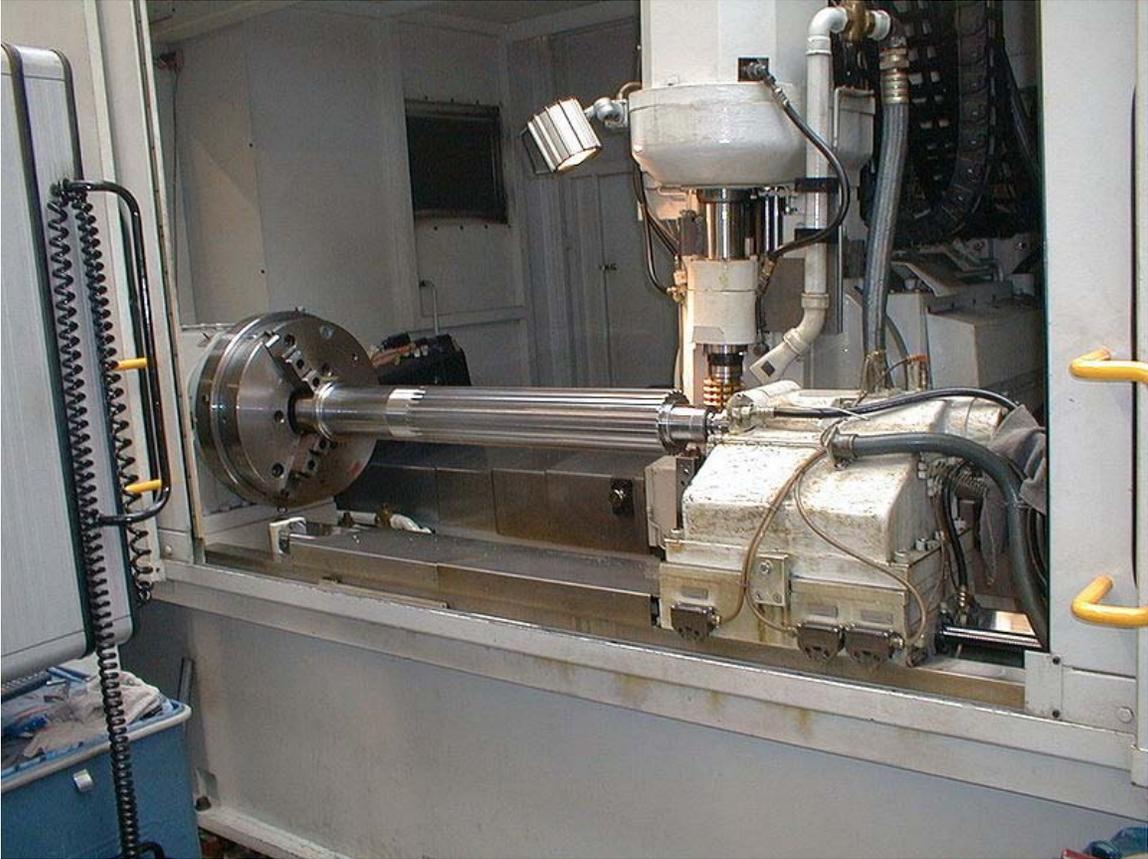
Process

Hobbing uses a hobbing machine with two non-parallel spindles, one mounted with a blank workpiece and the other with the hob. The angle between the hob's spindle and the workpiece's spindle varies, depending on the type of product being produced. For example, if a spur gear is being produced, then the hob is angled equal to the helix angle of the hob; if a helical gear is being produced then the angle must be increased by the same amount as the helix angle of the helical gear. The two shafts are rotated at a proportional ratio, which determines the number of teeth on the blank; for example, if the gear ratio is 40:1 the hob rotates 40 times to each turn of the blank, which produces 40 teeth in the blank. Note that the previous example only holds true for a single threaded hob; if the hob has multiple threads then the speed ratio must be multiplied by the number of threads on the hob. The hob is then fed up into workpiece until the correct tooth depth is obtained. Finally the hob is fed into the workpiece parallel to the blank's axis of rotation.

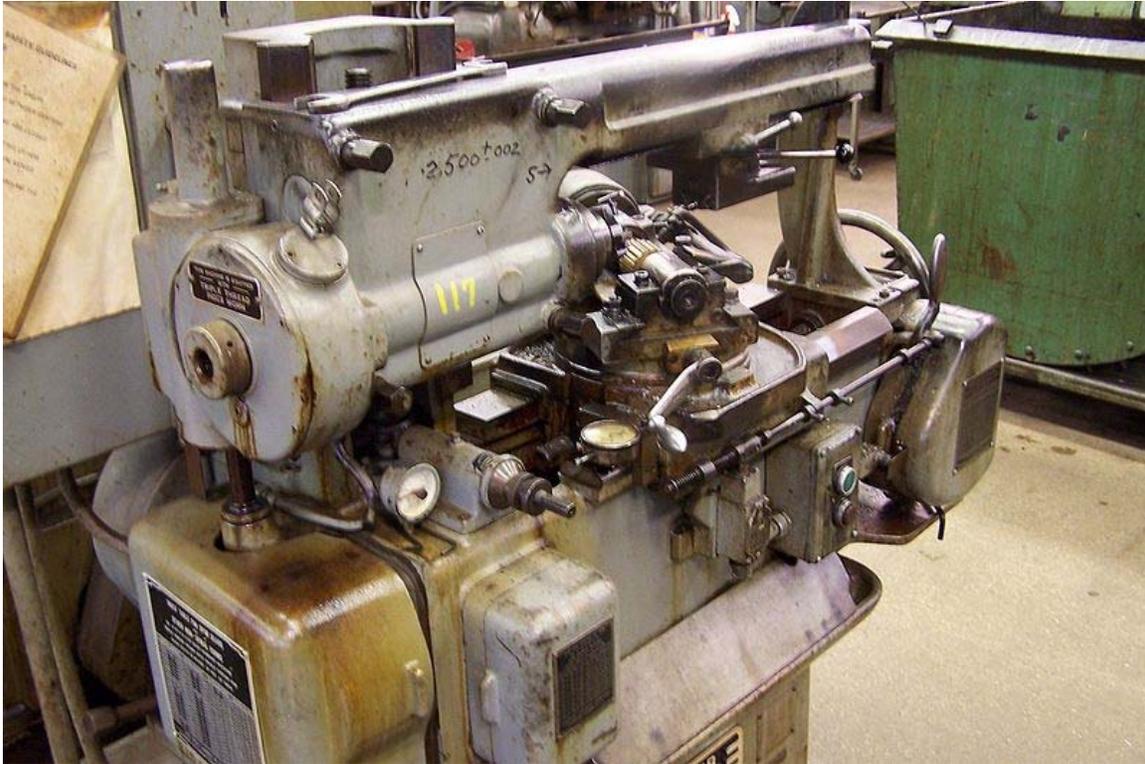
Up to five teeth can be cut into the workpiece at the same time. Oftentimes multiple gears are cut at the same time.

For larger gears the blank is usually gashed to the rough shape to make hobbing easier.

Equipment



A vertical hobbing machine



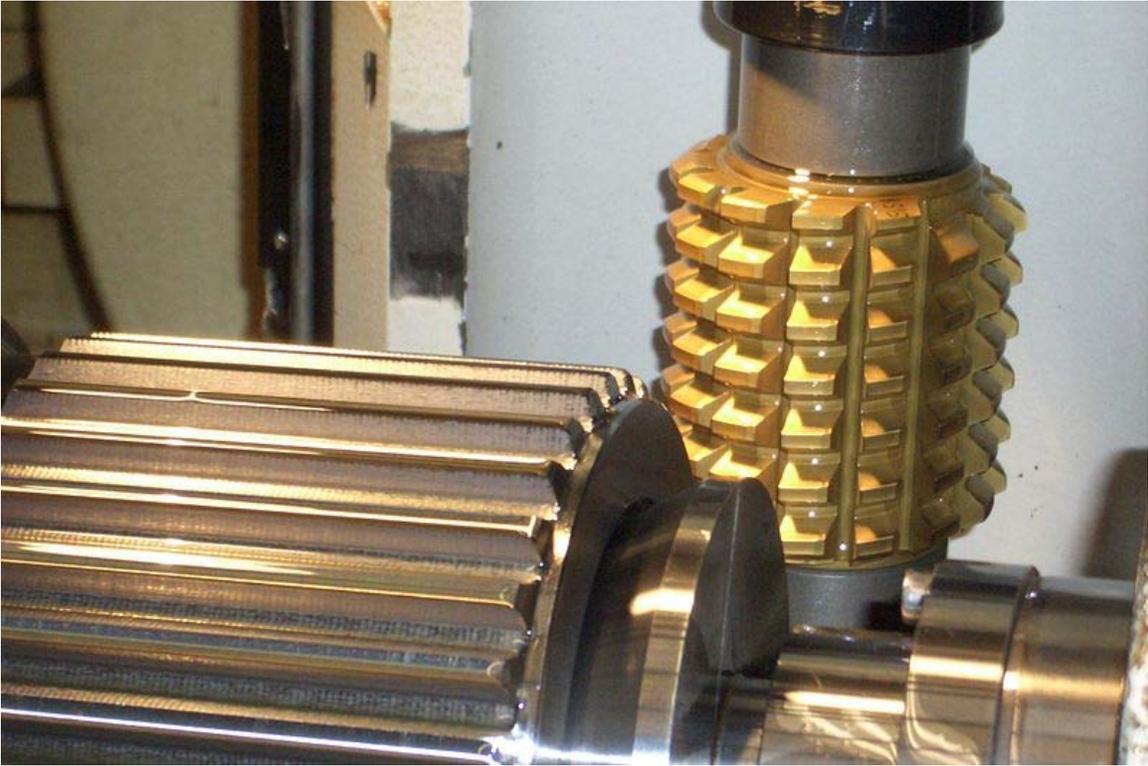
A horizontal hobbing machine

Modern hobbing machines, also known as *hobbers*, are fully automated machines that come in many sizes, because they need to be able to produce anything from tiny instrument gears up to 10 ft (3.0 m) diameter marine gears. Each gear hobbing machine typically consists of a chuck and tailstock, to hold the workpiece or a spindle, a spindle on which the hob is mounted, and a drive motor.

For a tooth profile which is a theoretical involute, the fundamental rack is straight-sided, with sides inclined at the pressure angle of the tooth form, with flat top and bottom. The necessary addendum correction to allow the use of small-numbered pinions can either be obtained by suitable modification of this rack to a cycloidal form at the tips, or by hobbing at other than the theoretical pitch circle diameter. Since the gear ratio between hob and blank is fixed, the resulting gear will have the correct pitch on the pitch circle, but the tooth thickness will not be equal to the space width.

Hobbing machines are characterised by the largest module or pitch diameter it can generate. For example, a 10 in (250 mm) capacity machine can generate gears with a 10 in pitch diameter and usually a maximum of a 10 in face width. Most hobbing machines are vertical hobbers, which means the blank is mounted vertically. Horizontal hobbing machines are usually used for cutting longer workpieces; i.e. cutting splines on the end of a shaft.

Hob



A gear hob in a hobbing machine with a finished gear.



The *hob* is the cutter used to cut the teeth into the workpiece. It is cylindrical in shape with helical cutting teeth. These teeth have grooves that run the length of the hob, which aid in cutting and chip removal. There are also special hobs designed for special gears such as the spline and sprocket gears.

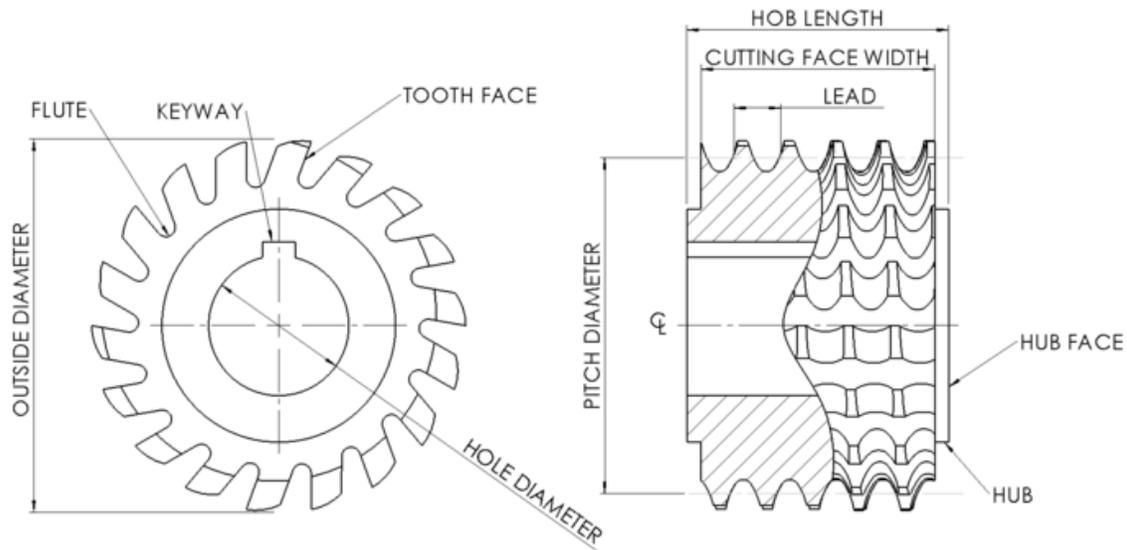
The cross-sectional shape of the hob teeth are almost the same shape as teeth of a rack gear that would be used with the finished product. There are slight changes to the shape for generating purposes, such as extending the hob's tooth length to create a clearance in the gear's roots. Each hob tooth is relieved on the back side to reduce friction.

Most hobs are single-thread hobs, but double-, and triple-thread hobs increase production rates. The downside is that they are not as accurate as single-thread hobs.

This list outlines types of hobs:

- Roller chain sprocket hobs
- Worm wheel hobs
- Spline hobs
- Chamfer hobs
- Spur and helical gear hobs
- Straight side spline hobs
- Involute spline hobs
- Serration hobs

- Semitopping gear hobs



Uses

Hobbing is used to make following types of finished goods:

- Cycloid gears
- Helical gears
- Involute gears
- Ratchets
- Splines
- Sprockets
- Spur gears
- Worm gears

Hobbing is used to produce most throated worm wheels, but certain tooth profiles cannot be hobbled. If any portion of the hob profile is perpendicular to the axis then it will have no cutting clearance generated by the usual backing off process, and it will not cut well.

Cycloidal forms

For cycloidal gears (as used in BS978-2 Specification for fine pitch gears) and cycloidal-type gears each module, ratio and number of teeth in the pinion requires a different hobbing cutter so the technique is only suitable for large volume production.

To circumvent this problem a special war-time emergency circular arc gear standard was produced giving a series of close to cycloidal forms which could be cut with a single hob for each module for eight teeth and upwards to economize on cutter manufacturing

resources. A variant on this is still included in BS978-2a (Gears for instruments and clockwork mechanisms. Cycloidal type gears. Double circular arc type gears).

Tolerances of concentricity of the hob limit the lower modules which can be cut practically by hobbing to about 0.5 module.

History

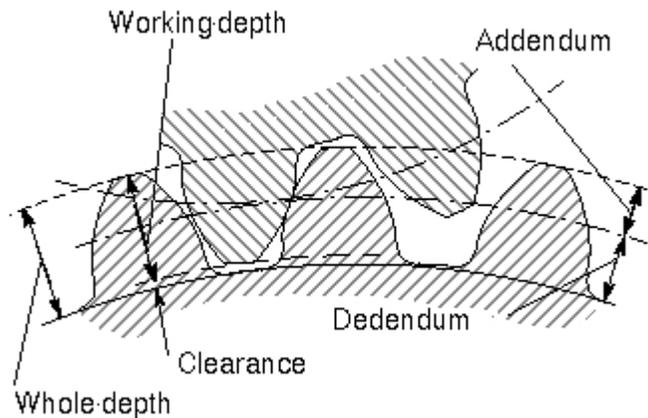
Many manufacturing firms that maintain museums of how products were produced in times past will have examples of manual gear hobs that helped to produce gears prior to the gears of the 19th century and earlier. Along with these completely manual gear hobs will be samples of some of the first semi-automated gear hobs, and finally examples of more recent technology that demonstrates the fully automated process that modern gear hobs use to produce gears today. A few producers of gear hobs also have interesting literature on the history of gear hobs, including details about how modern gear hobs can produce thousands of gears in a single hour.

Chapter 7

List of Gear Nomenclature

Gears have a wide range of unique terminology known as **gear nomenclature**. Many of the terms defined cite the same reference work.

Addendum



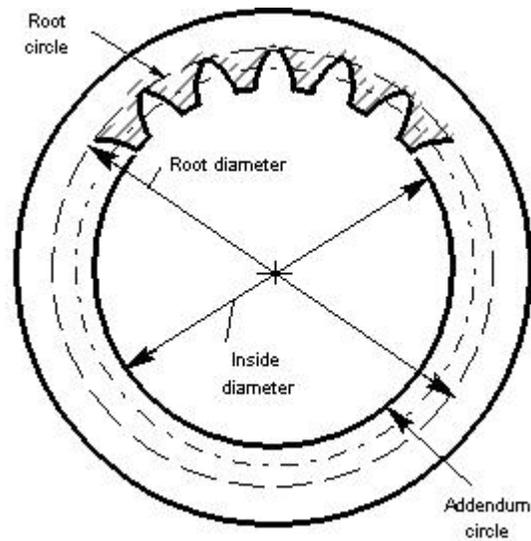
Principal dimensions

The **addendum** is the height by which a tooth of a gear projects beyond (outside for external, or inside for internal) the standard pitch circle or pitch line; also, the radial distance between the pitch circle and the addendum circle.

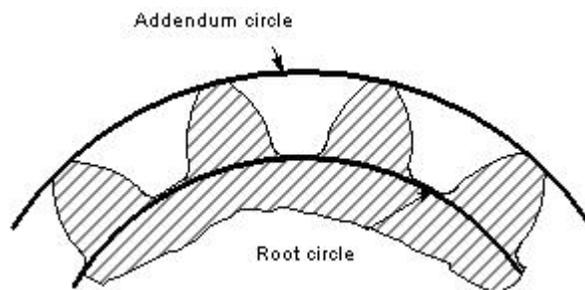
Addendum angle

Addendum angle in a bevel gear, is the angle between elements of the face cone and pitch cone.

Addendum circle



Internal gear diameters

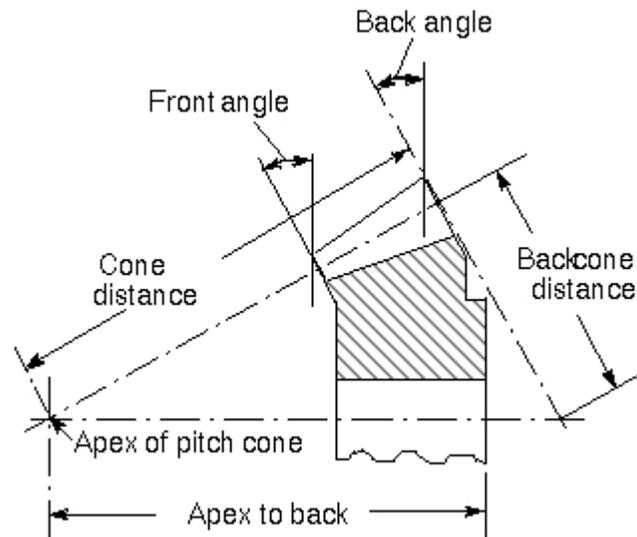


Root circle

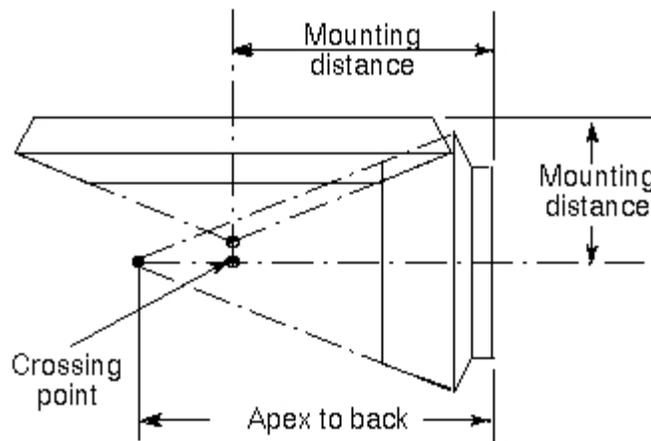
The **addendum circle** coincides with the tops of the teeth of a gear and is concentric with the standard (reference) pitch circle and radially distant from it by the amount of the addendum. For external gears, the addendum circle lies on the outside cylinder while on internal gears the addendum circle lies on the internal cylinder.

Angle of pressure

Apex to back



Apex to back



Hypoid Gear and Pinion

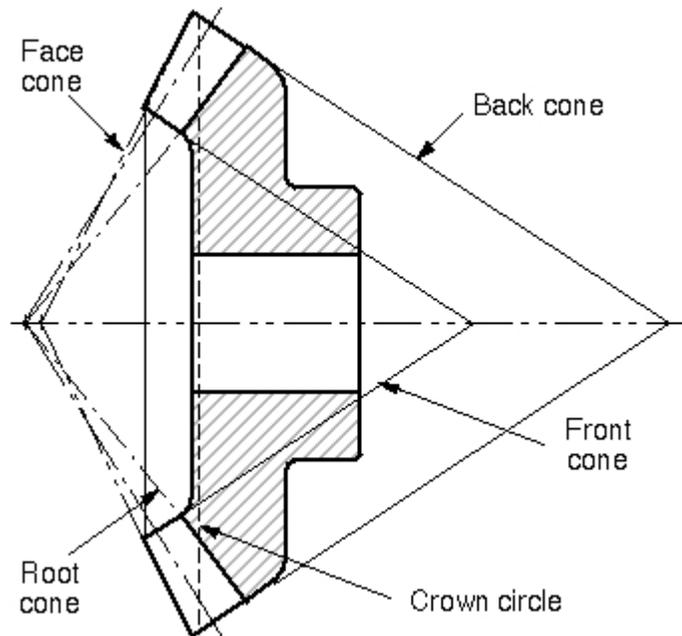
Mounting distance

Apex to back, in a bevel gear or hypoid gear, is the distance in the direction of the axis from the apex of the pitch cone to a locating surface at the back of the blank.

Back angle

The **back angle** of a bevel gear is the angle between an element of the back cone and a plane of rotation, and usually is equal to the pitch angle.

Back cone



Principal dimensions

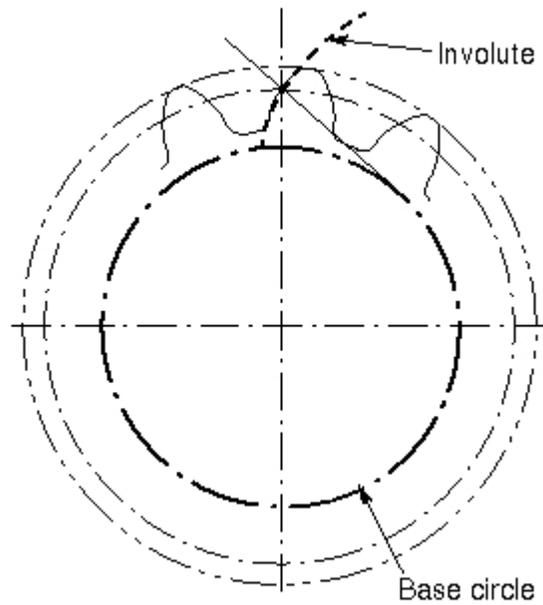
The **back cone** of a bevel or hypoid gear is an imaginary cone tangent to the outer ends of the teeth, with its elements perpendicular to those of the pitch cone. The surface of the gear blank at the outer ends of the teeth is customarily formed to such a back cone.

Back cone distance

Back cone distance in a bevel gear is the distance along an element of the back cone from its apex to the pitch cone.

Backlash

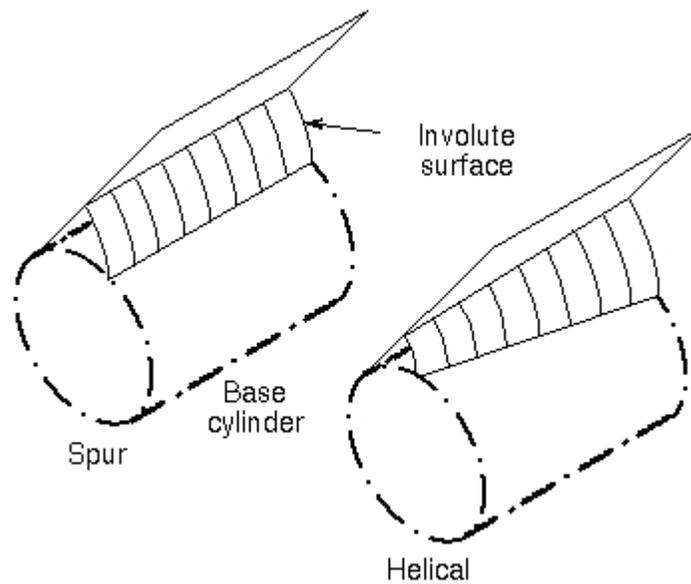
Base circle



Involute teeth

The **base circle** of an involute gear is the circle from which involute tooth profiles are derived.

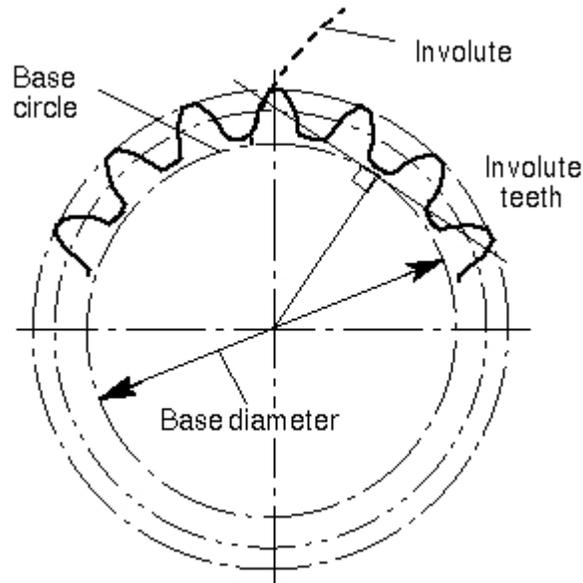
Base cylinder



Base cylinder

The **base cylinder** corresponds to the base circle, and is the cylinder from which involute tooth surfaces are developed.

Base diameter



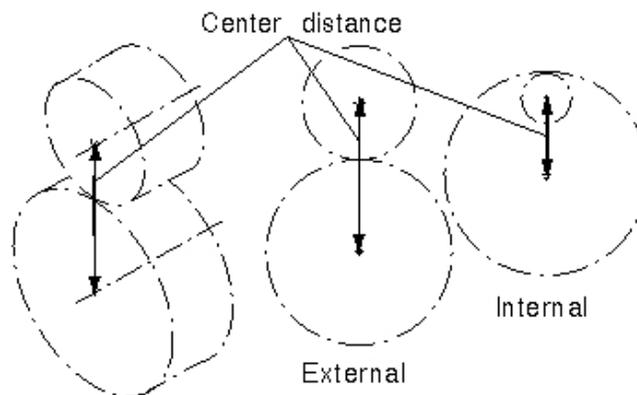
Base diameter

The **base diameter** of an involute gear is the diameter of the base circle.

Bull gear

The term **bull gear** is used to refer to the larger of two spur gears that are in engagement in any machine. The smaller gear is usually referred to as a pinion.

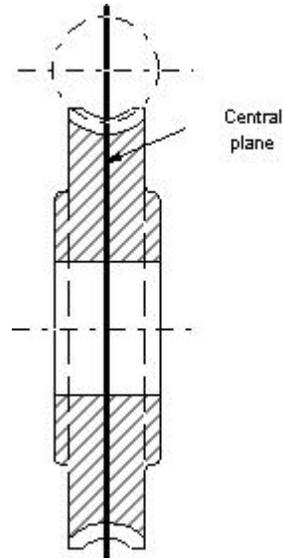
Center distance



Center distance

Center distance (operating) is the shortest distance between non-intersecting axes. It is measured along the mutual perpendicular to the axes, called the line of centers. It applies to spur gears, parallel axis or crossed axis helical gears, and worm gearing.

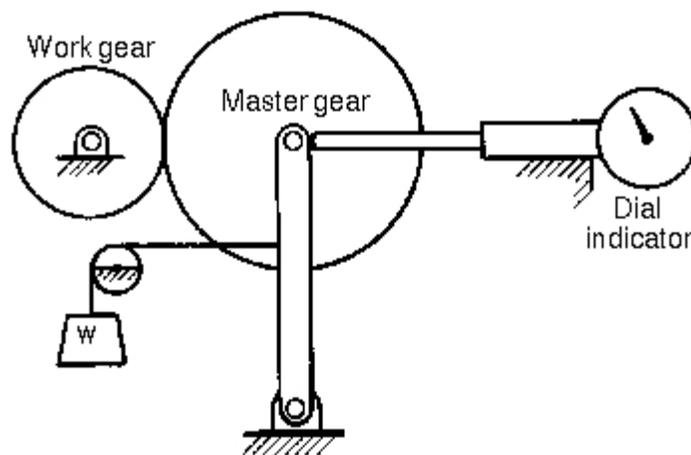
Central plane



Central plane

The **central plane** of a worm gear is perpendicular to the gear axis and contains the common perpendicular of the gear and worm axes. In the usual case with axes at right angles, it contains the worm axis.

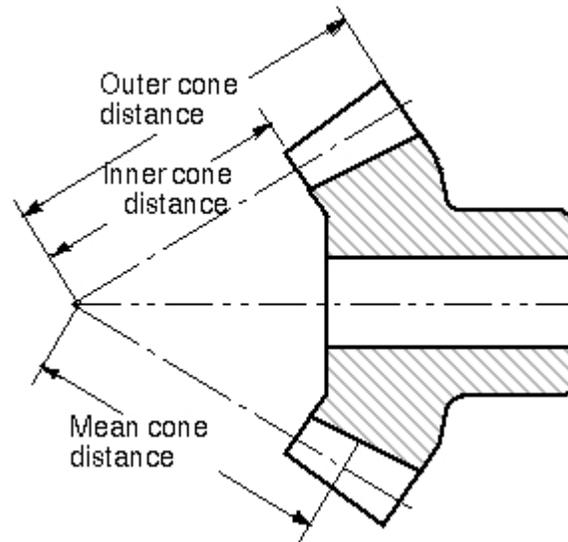
Composite action test



Schematic of the composite action test

The **composite action test** (double flank) is a method of inspection in which the work gear is rolled in tight double flank contact with a master gear or a specified gear, in order to determine (radial) composite variations (deviations). The composite action test must be made on a variable center distance composite action test device.

Cone distance



Cone distance

Cone distance in a bevel gear is the general term for the distance along an element of the pitch cone from the apex to any given position in the teeth.

Outer cone distance in bevel gears is the distance from the apex of the pitch cone to the outer ends of the teeth. When not otherwise specified, the short term cone distance is understood to be outer cone distance.

Mean cone distance in bevel gears is the distance from the apex of the pitch cone to the middle of the face width.

Inner cone distance in bevel gears is the distance from the apex of the pitch cone to the inner ends of the teeth.

Conjugate gears

Conjugate gears transmit uniform rotary motion from one shaft to another by means of gear teeth. The normals to the profiles of these teeth, at all points of contact, must pass through a fixed point in the common centerline of the two shafts.

Crossed helical gear

A **crossed helical gear** is a gear that operate on non-intersecting, non-parallel axes.

The term crossed helical gears has superseded the term *spiral gears*. There is theoretically point contact between the teeth at any instant. They have teeth of the same or different helix angles, of the same or opposite hand. A combination of spur and helical or other types can operate on crossed axes.

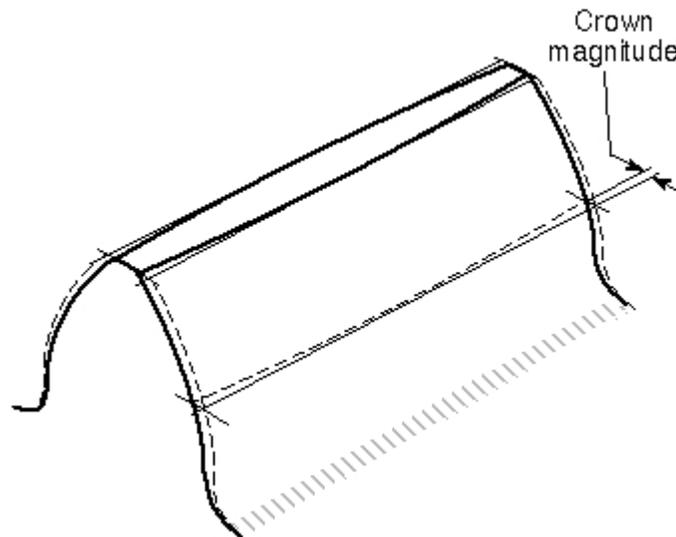
Crossing point

The **crossing point** is the point of intersection of bevel gear axes; also the apparent point of intersection of the axes in hypoid gears, crossed helical gears, worm gears, and offset face gears, when projected to a plane parallel to both axes.

Crown circle

The **crown circle** in a bevel or hypoid gear is the circle of intersection of the back cone and face cone.

Crowned teeth



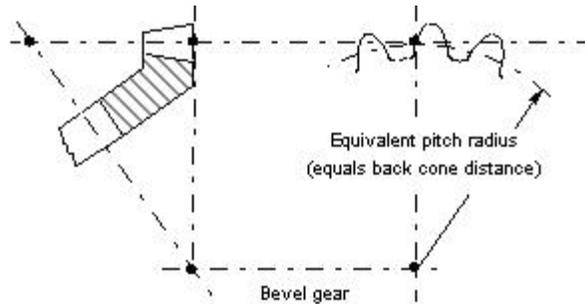
Crowned gear

Crowned teeth have surfaces modified in the lengthwise direction to produce localized contact or to prevent contact at their ends.

Dedendum angle

Dedendum angle in a bevel gear, is the angle between elements of the root cone and pitch cone.

Equivalent pitch radius



Back cone equivalent

Equivalent pitch radius is the radius of the pitch circle in a cross section of gear teeth in any plane other than a plane of rotation. It is properly the radius of curvature of the pitch surface in the given cross section. Examples of such sections are the transverse section of bevel gear teeth and the normal section of helical teeth.

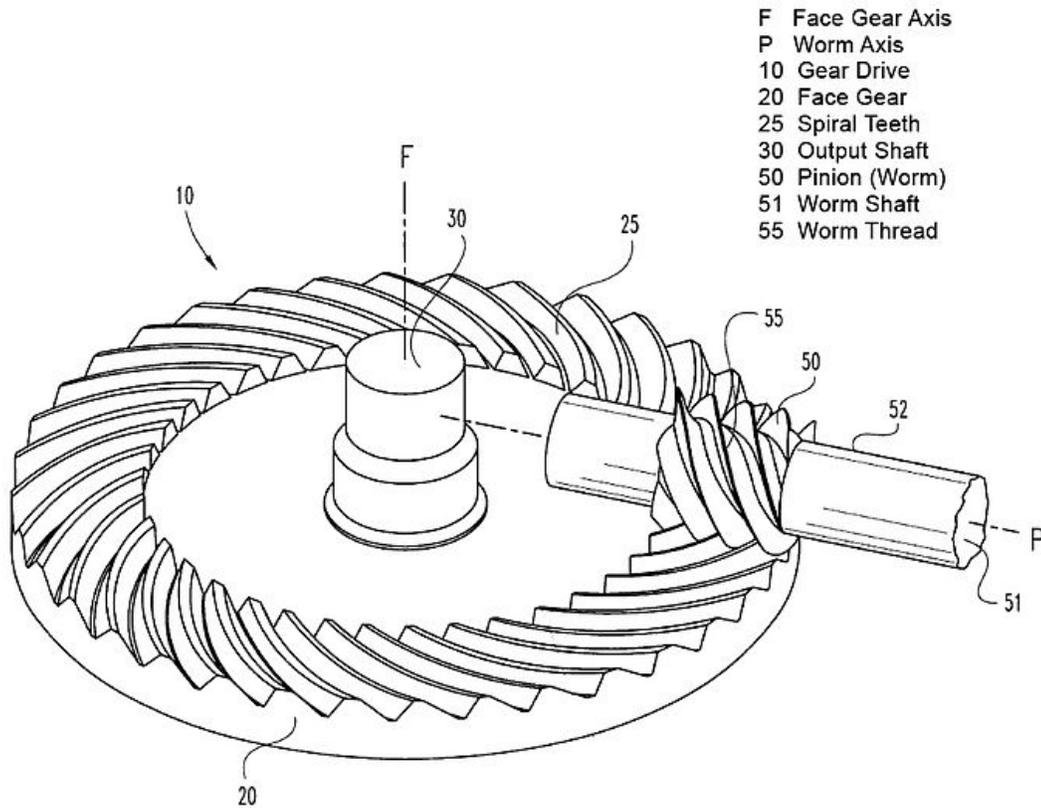
Face (tip) angle

Face (tip) angle in a bevel or hypoid gear, is the angle between an element of the face cone and its axis.

Face cone

The **face cone**, also known as the **tip cone** is the imaginary surface that coincides with the tops of the teeth of a bevel or hypoid gear.

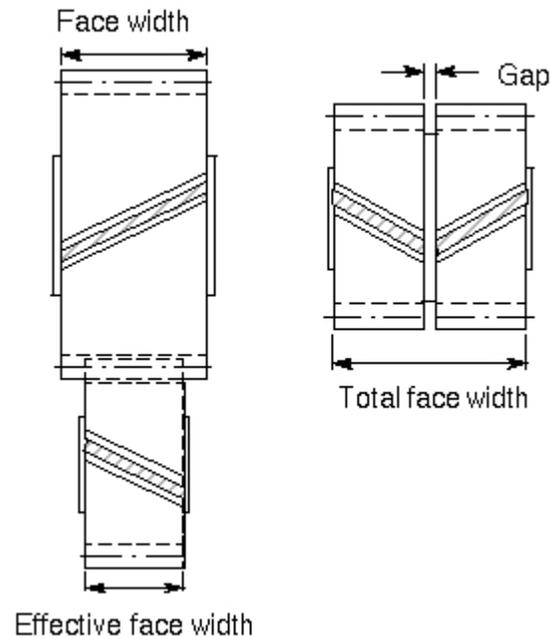
Face gear



Face worm gear

A **face gear** set typically consists of a disk-shaped gear, grooved on at least one face, in combination with a spur, helical, or conical pinion. A face gear has a planar pitch surface and a planar root surface, both of which are perpendicular to the axis of rotation. It can also be referred to as a **face wheel**, **crown gear**, **crown wheel**, **contrate gear** or **contrate wheel**.

Face width



Face width

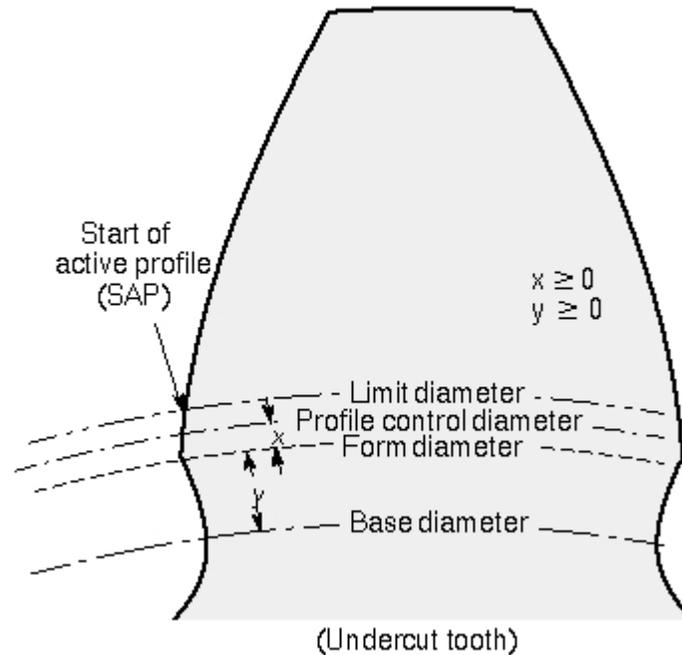
The **face width** of a gear is the length of teeth in an axial plane. For double helical, it does not include the gap.

Total face width is the actual dimension of a gear blank including the portion that exceeds the effective face width, or as in double helical gears where the total face width includes any distance or gap separating right hand and left hand helices.

For a cylindrical gear, effective face width is the portion that contacts the mating teeth. One member of a pair of gears may engage only a portion of its mate.

For a bevel gear, different definitions for effective face width are applicable.

Form diameter



Form diameter

Form diameter is the diameter of a circle at which the trochoid (fillet curve) produced by the tooling intersects, or joins, the involute or specified profile. Although these terms are not preferred, it is also known as the true involute form diameter (TIF), start of involute diameter (SOI), or when undercut exists, as the undercut diameter. This diameter cannot be less than the base circle diameter.

Front angle

The **front angle**, in a bevel gear, denotes the angle between an element of the front cone and a plane of rotation, and usually equals the pitch angle.

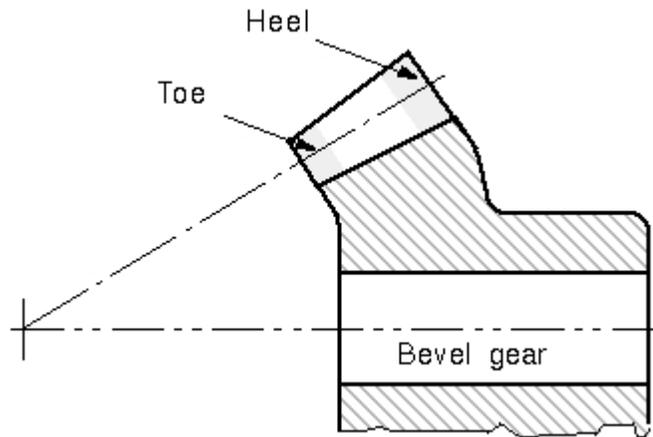
Front cone

The **front cone** of a hypoid or bevel gear is an imaginary cone tangent to the inner ends of the teeth, with its elements perpendicular to those of the pitch cone. The surface of the gear blank at the inner ends of the teeth is customarily formed to such a front cone, but sometimes may be a plane on a pinion or a cylinder in a nearly flat gear.

Gear center

A **gear center** is the center of the pitch circle.

Heel



Heel and toe

The **heel** of a tooth on a bevel gear or pinion is the portion of the tooth surface near its outer end.

The **toe** of a tooth on a bevel gear or pinion is the portion of the tooth surface near its inner end.

Helical rack

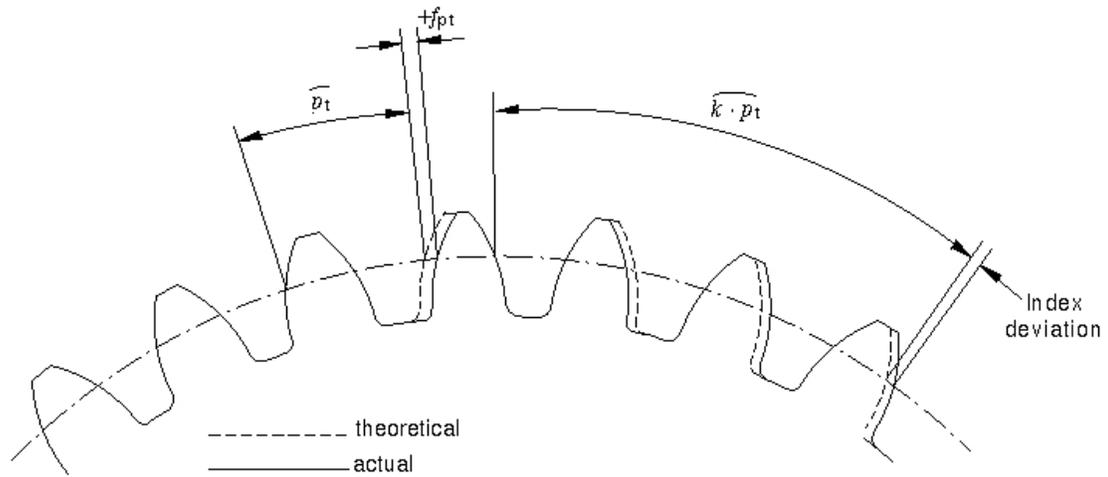
A **helical rack** has a planar pitch surface and teeth that are oblique to the direction of motion.

Index deviation

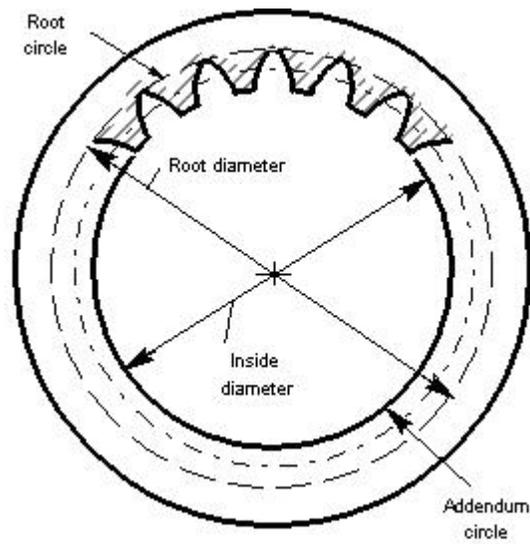
The displacement of any tooth flank from its theoretical position, relative to a datum tooth flank.

Distinction is made as to the direction and algebraic sign of this reading. A condition wherein the actual tooth flank position was nearer to the datum tooth flank, in the specified measuring path direction (clockwise or counterclockwise), than the theoretical position would be considered a minus (-) deviation. A condition wherein the actual tooth flank position was farther from the datum tooth flank, in the specified measuring path direction, than the theoretical position would be considered a plus (+) deviation.

The direction of tolerancing for index deviation along the arc of the tolerance diameter circle within the transverse plane.



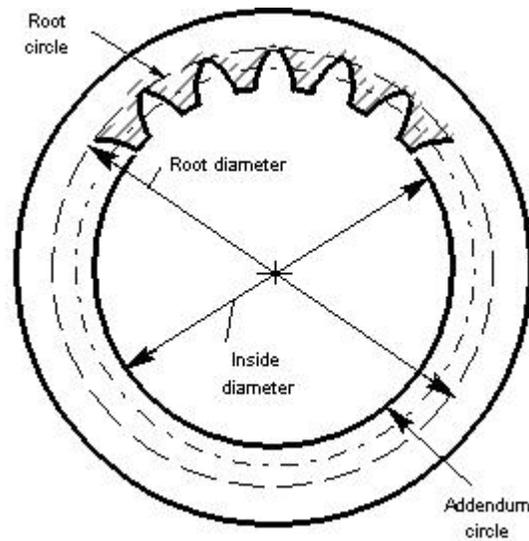
Inside cylinder



Diameters, Internal Gear

The **inside cylinder** is the surface that coincides with the tops of the teeth of an internal cylindrical gear.

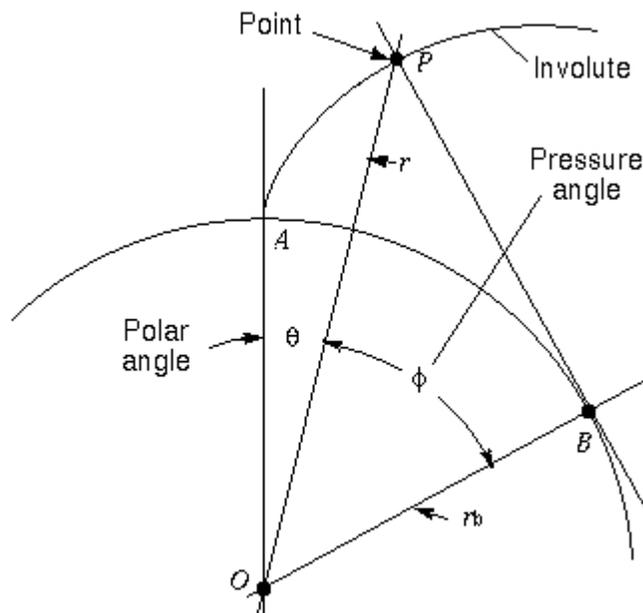
Inside diameter



Internal gear diameters

Inside diameter is the diameter of the addendum circle of an internal gear.

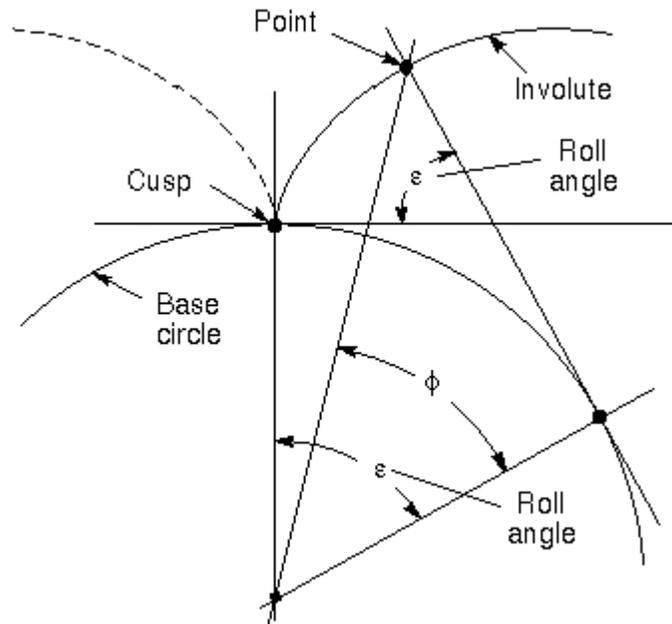
Involute polar angle



Involute polar angle

Expressed as θ , the **involute polar angle** is the angle between a radius vector to a point, P , on an involute curve and a radial line to the intersection, A , of the curve with the base circle.

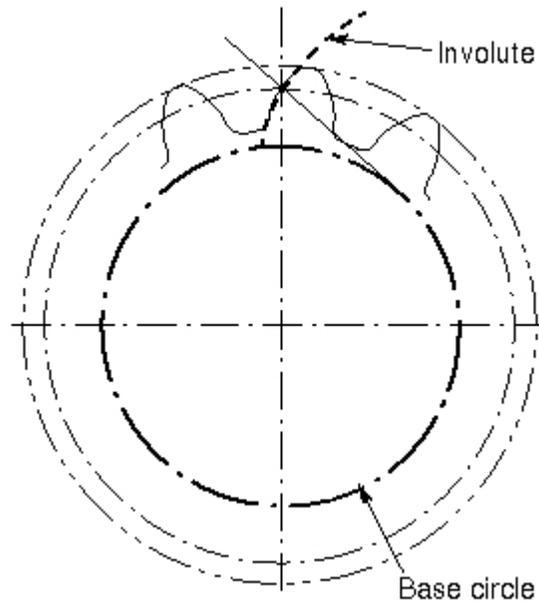
Involute roll angle



Involute roll angle

Expressed as ϵ , the **involute roll angle** is the angle whose arc on the base circle of radius unity equals the tangent of the pressure angle at a selected point on the involute.

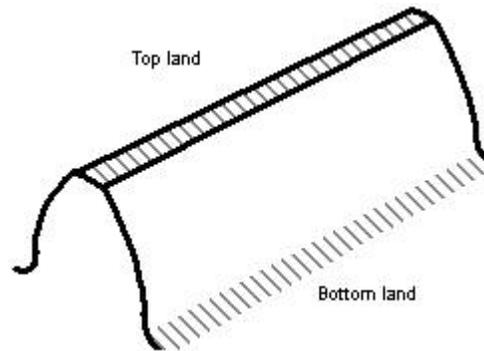
Involute teeth



Involute teeth

Involute teeth of spur gears, helical gears, and worms are those in which the profile in a transverse plane (exclusive of the fillet curve) is the involute of a circle.

Lands



Top and bottom lands

Bottom land

The **bottom land** is the surface at the bottom of a gear tooth space adjoining the fillet.

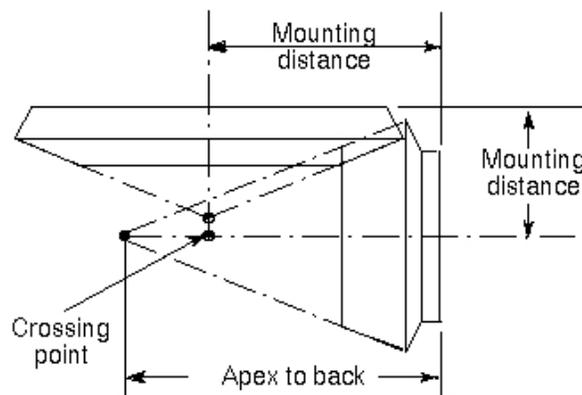
Top land

Top land is the (sometimes flat) surface of the top of a gear tooth.

Line of centers

The **line of centers** connects the centers of the pitch circles of two engaging gears; it is also the common perpendicular of the axes in crossed helical gears and wormgears. When one of the gears is a rack, the line of centers is perpendicular to its pitch line.

Mounting distance



Hypoid Gear and Pinion

Mounting distance

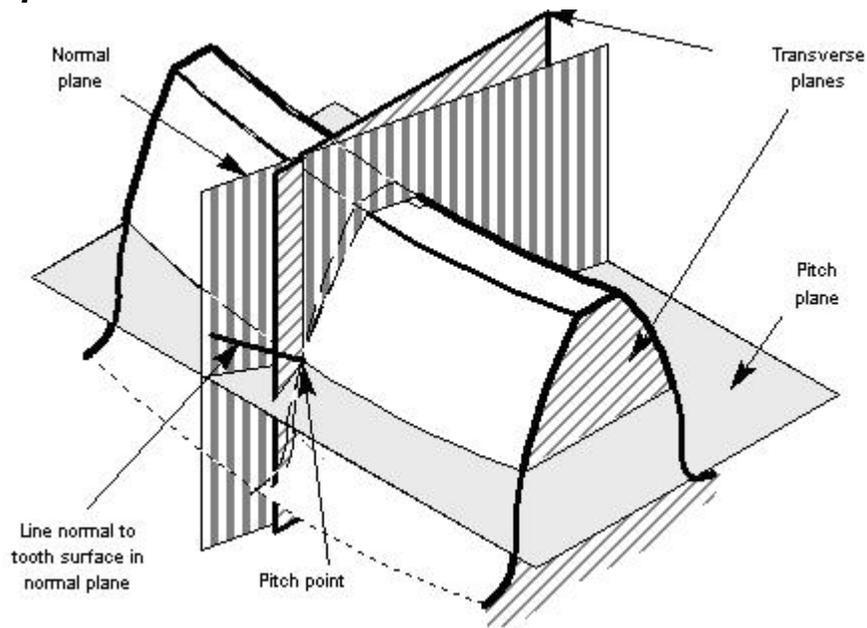
Mounting distance, for assembling bevel gears or hypoid gears, is the distance from the crossing point of the axes to a locating surface of a gear, which may be at either back or front.

Normal module

Normal module is the value of the module in a normal plane of a helical gear or worm.

$$m_n = m_t \cos \beta$$

Normal plane



Planes at a pitch point on a helical tooth

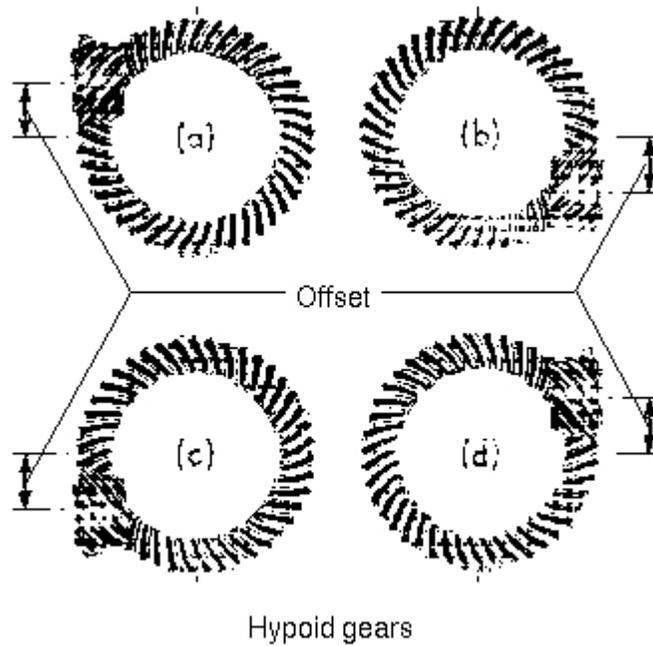
A **normal plane** is normal to a tooth surface at a pitch point, and perpendicular to the pitch plane. In a helical rack, a normal plane is normal to all the teeth it intersects. In a helical gear, however, a plane can be normal to only one tooth at a point lying in the plane surface. At such a point, the normal plane contains the line normal to the tooth surface.

Important positions of a normal plane in tooth measurement and tool design of helical teeth and worm threads are:

1. the plane normal to the pitch helix at side of tooth;
2. the plane normal to the pitch helix at center of tooth;
3. the plane normal to the pitch helix at center of space between two teeth

In a spiral bevel gear, one of the positions of a normal plane is at a mean point and the plane is normal to the tooth trace.

Offset

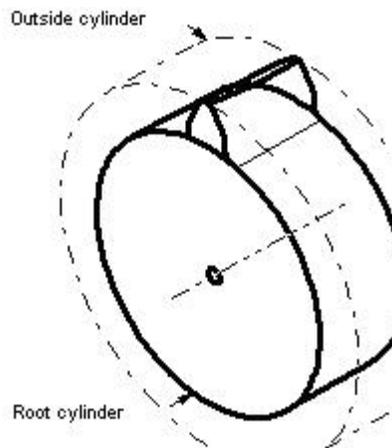


Offset

Offset is the perpendicular distance between the axes of hypoid gears or offset face gears.

In the diagram to the right, (a) and (b) are referred to as having an offset *below center*, while those in (c) and (d) have an offset *above center*. In determining the direction of offset, it is customary to look at the gear with the pinion at the right. For below center offset the pinion has a left hand spiral, and for above center offset the pinion has a right hand spiral.

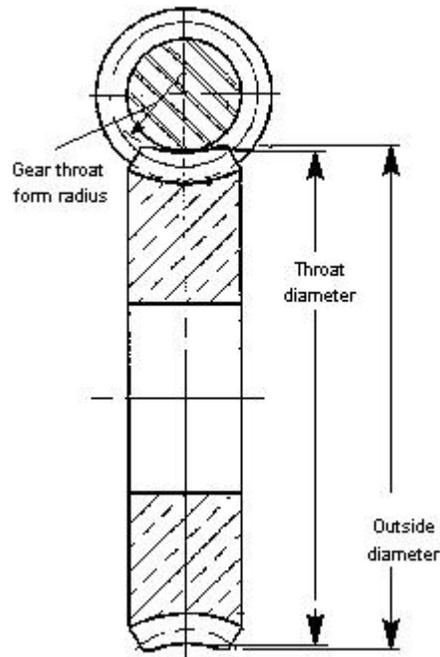
Outside cylinder



Cylindrical surfaces

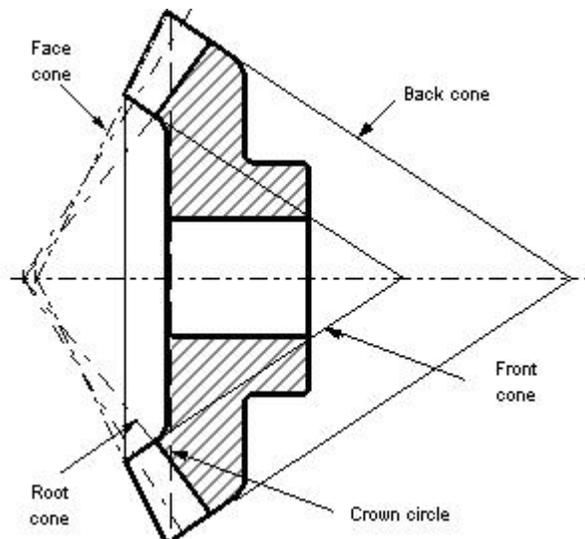
The **outside** (tip or addendum) **cylinder** is the surface that coincides with the tops of the teeth of an external cylindrical gear.

Outside diameter



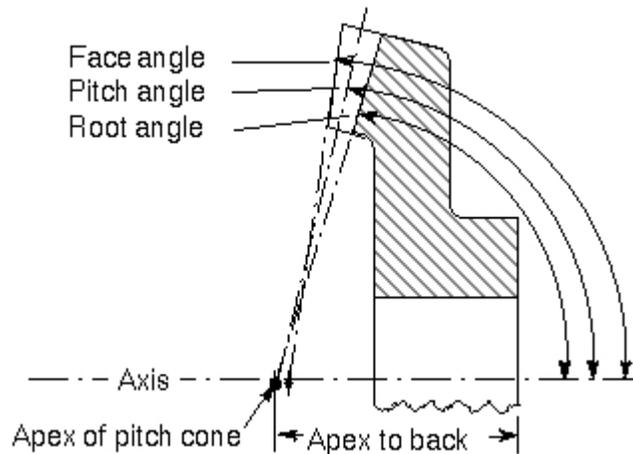
Wormgear diameters

The **outside diameter** of a gear is the diameter of the addendum (tip) circle. In a bevel gear it is the diameter of the crown circle. In a throated wormgear it is the maximum diameter of the blank. The term applies to external gears.

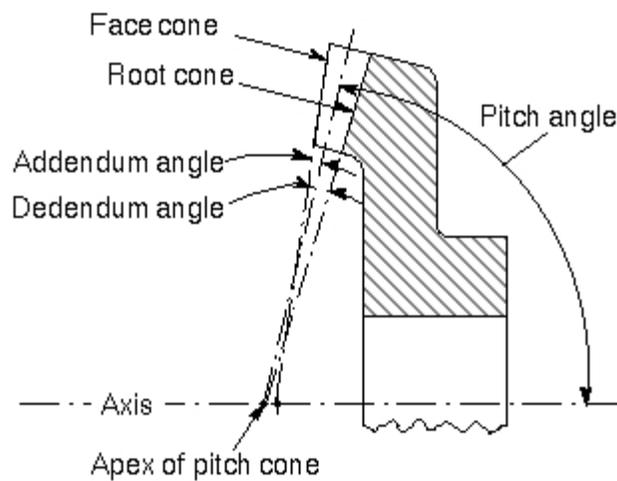


Conical surfaces

Pitch angle



Angle relationships



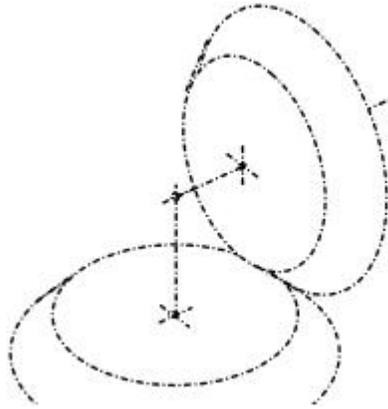
Angles

Pitch angle in bevel gears, is the angle between an element of a pitch cone and its axis. In external and internal bevel gears, the pitch angles are respectively less than and greater than 90 degrees.

Pitch circle

A **pitch circle** (operating) is the curve of intersection of a pitch surface of revolution and a plane of rotation. It is the imaginary circle that rolls without slipping with a pitch circle of a mating gear.

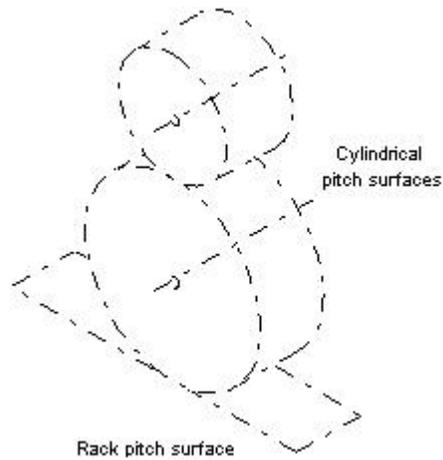
Pitch cone



Pitch cones

A **pitch cone** is the imaginary cone in a bevel gear that rolls without slipping on a pitch surface of another gear.

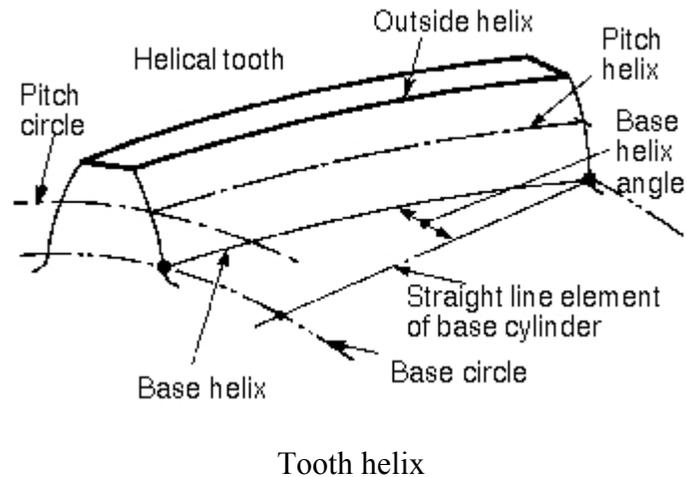
Pitch cylinder



Pitch cylinder

A **pitch cylinder** is the imaginary cylinder in a spur or helical gear that rolls without slipping on a pitch plane or pitch cylinder of another gear.

Pitch helix



The **pitch helix** is the intersection of the tooth surface and the pitch cylinder of a helical gear or cylindrical worm.

Base helix

The **base helix** of a helical, involute gear or involute worm lies on its base cylinder.

Base helix angle

Base helix angle is the helix angle on the base cylinder of involute helical teeth or threads.

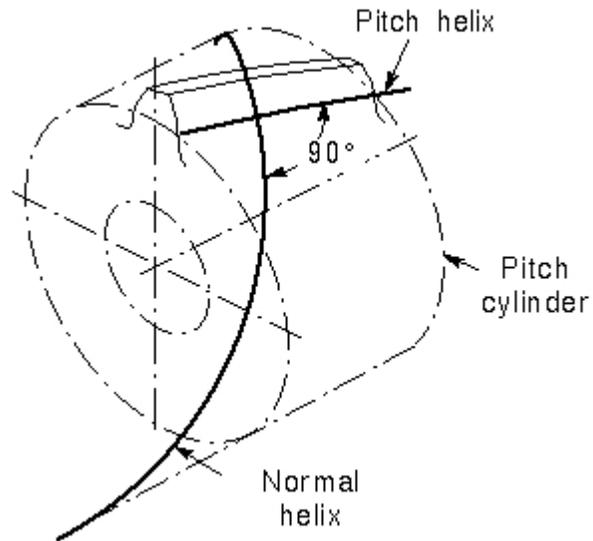
Base lead angle

Base lead angle is the lead angle on the base cylinder. It is the complement of the base helix angle.

Outside helix

The **outside (tip or addendum) helix** is the intersection of the tooth surface and the outside cylinder of a helical gear or cylindrical worm.

Outside helix angle



Normal helix

Outside helix angle is the helix angle on the outside cylinder.

Outside lead angle

Outside lead angle is the lead angle on the outside cylinder. It is the complement of the outside helix angle.

Normal helix

A **normal helix** is a helix on the pitch cylinder, normal to the pitch helix.

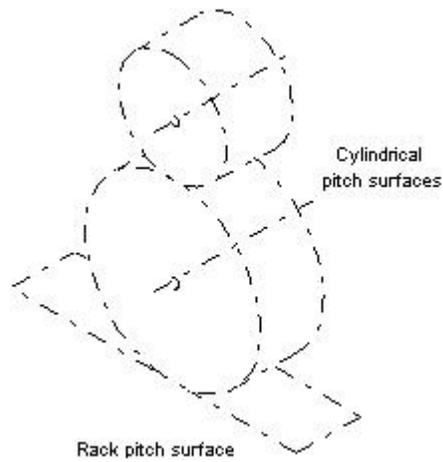
Pitch line

The **pitch line** corresponds, in the cross section of a rack, to the pitch circle (operating) in the cross section of a gear.

Pitch point

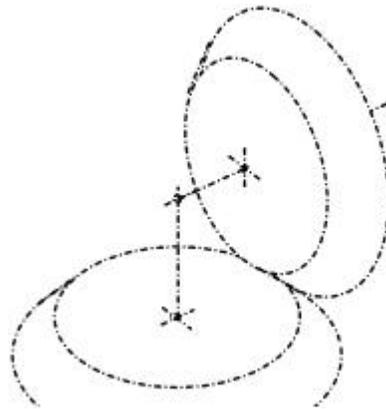
The **pitch point** is the point of tangency of two pitch circles (or of a pitch circle and pitch line) and is on the line of centers.

Pitch surfaces



Pitch surfaces

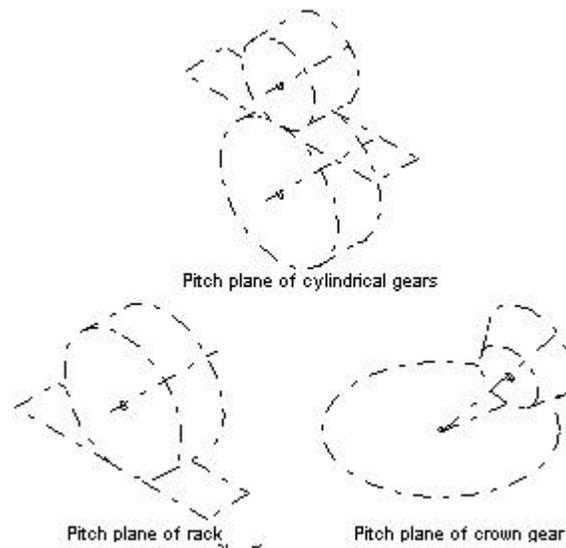
Pitch surfaces are the imaginary planes, cylinders, or cones that roll together without slipping. For a constant velocity ratio, the pitch cylinders and pitch cones are circular.



Pitch cones

Planes

Pitch plane



Pitch planes

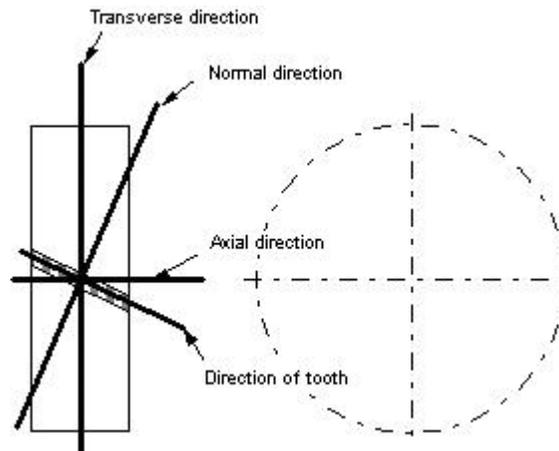
The **pitch plane** of a pair of gears is the plane perpendicular to the axial plane and tangent to the pitch surfaces. A pitch plane in an individual gear may be any plane tangent to its pitch surface.

The pitch plane of a rack or in a crown gear is the imaginary planar surface that rolls without slipping with a pitch cylinder or pitch cone of another gear. The pitch plane of a rack or crown gear is also the pitch surface.

Transverse plane

The **transverse plane** is perpendicular to the axial plane and to the pitch plane. In gears with parallel axes, the transverse and the plane of rotation coincide.

Principal directions



Principal directions

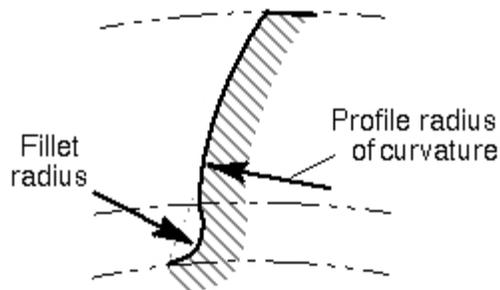
Principal directions are directions in the pitch plane, and correspond to the principal cross sections of a tooth.

The axial direction is a direction parallel to an axis.

The transverse direction is a direction within a transverse plane.

The normal direction is a direction within a normal plane.

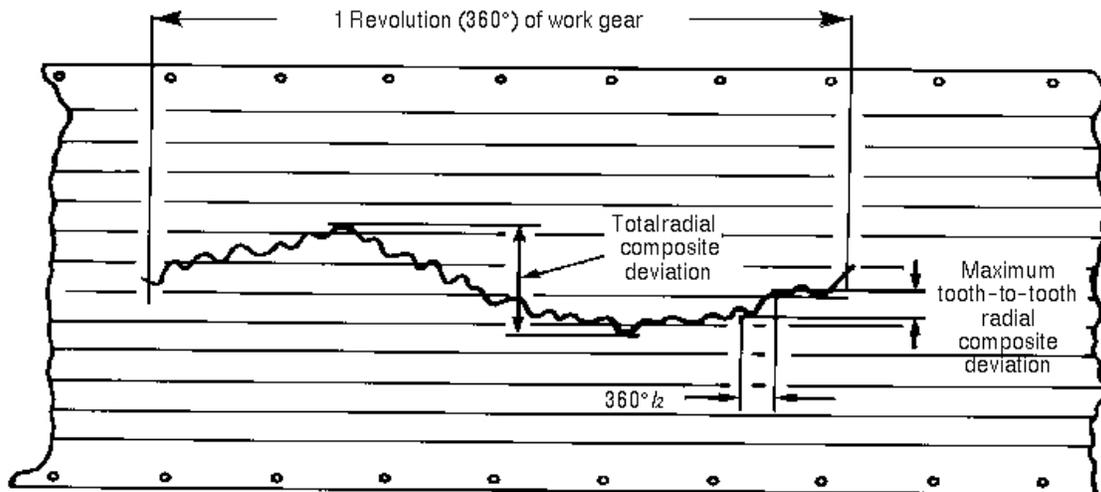
Profile radius of curvature



Fillet radius

Profile radius of curvature is the radius of curvature of a tooth profile, usually at the pitch point or a point of contact. It varies continuously along the involute profile.

Radial composite deviation



Total composite variation trace

Tooth-to-tooth **radial composite deviation** (double flank) is the greatest change in center distance while the gear being tested is rotated through any angle of $360^\circ/z$ during double flank composite action test.

Tooth-to-tooth radial composite tolerance (double flank) is the permissible amount of tooth-to-tooth radial composite deviation.

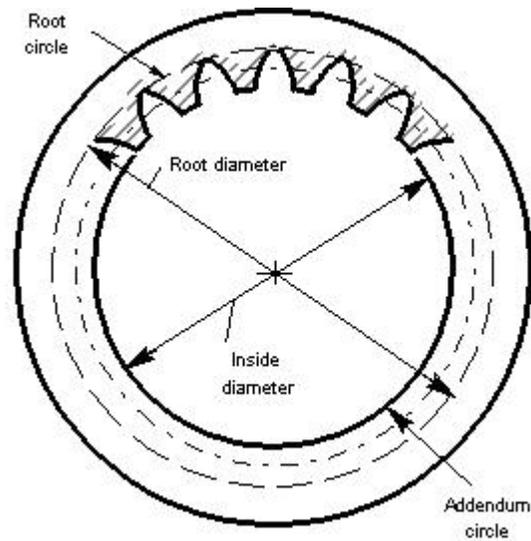
Total radial composite deviation (double flank) is the total change in center distance while the gear being tested is rotated one complete revolution during a double flank composite action test.

Total radial composite tolerance (double flank) is the permissible amount of total radial composite deviation.

Root angle

Root angle in a bevel or hypoid gear, is the angle between an element of the root cone and its axis.

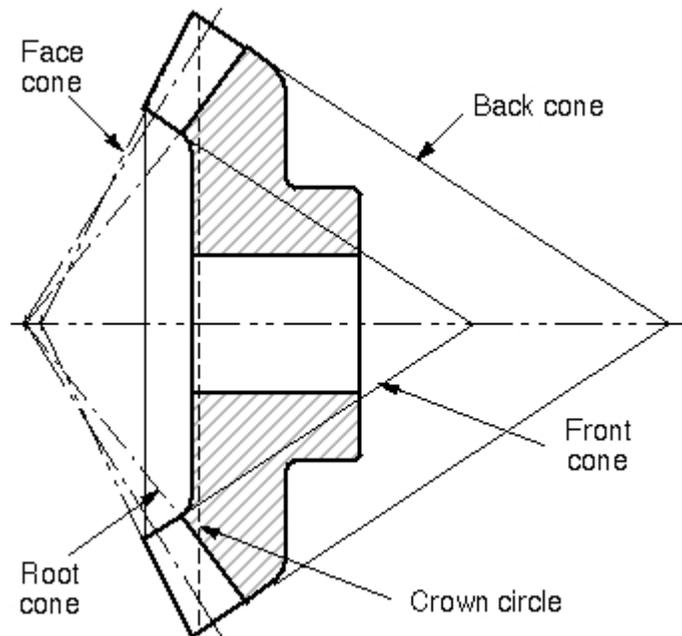
Root circle



Internal gear diameters

The **root circle** coincides with the bottoms of the tooth spaces.

Root cone



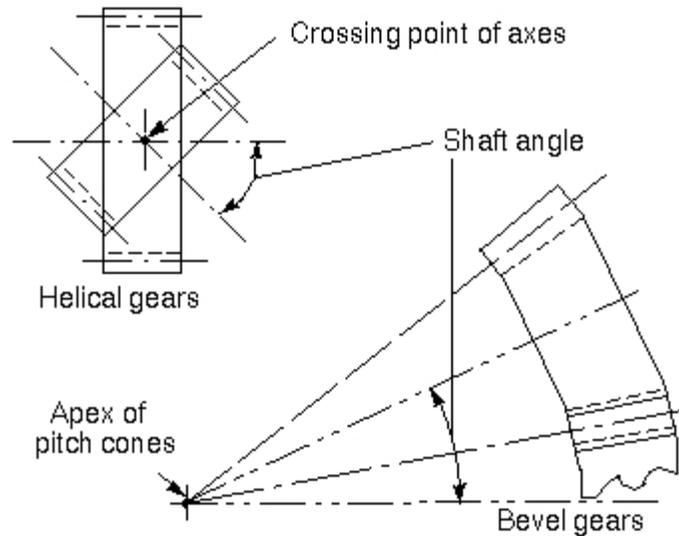
Principal dimensions

The **root cone** is the imaginary surface that coincides with the bottoms of the tooth spaces in a bevel or hypoid gear.

Root cylinder

The **root cylinder** is the imaginary surface that coincides with the bottoms of the tooth spaces in a cylindrical gear.

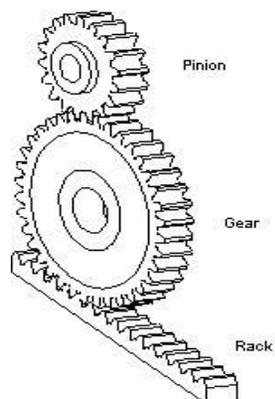
Shaft angle



Shaft angle

A **shaft angle** is the angle between the axes of two non-parallel gear shafts. In a pair of crossed helical gears, the shaft angle lies between the oppositely rotating portions of two shafts. This applies also in the case of worm gearing. In bevel gears, the shaft angle is the sum of the two pitch angles. In hypoid gears, the shaft angle is given when starting a design, and it does not have a fixed relation to the pitch angles and spiral angles.

Spur gear



Spur gear

A **spur gear** has a cylindrical pitch surface and teeth that are parallel to the axis.

Spur rack

A **spur rack** has a planar pitch surface and straight teeth that are at right angles to the direction of motion.

Standard pitch circle

The **standard pitch circle** is the circle which intersects the involute at the point where the pressure angle is equal to the profile angle of the basic rack.

Standard pitch diameter

The **standard reference pitch diameter** is the diameter of the standard pitch circle. In spur and helical gears, unless otherwise specified, the standard pitch diameter is related to the number of teeth and the standard transverse pitch. The diameter can be roughly estimated by taking the average of the diameter measuring the tips of the gear teeth and the base of the gear teeth.

The pitch diameter is useful in determining the spacing between gear centers because proper spacing of gears implies tangent pitch circles. The pitch diameters of two gears may be used to calculate the gear ratio in the same way the number of teeth is used.

$$d = \frac{N}{P_d} = \frac{pN}{\pi} \quad \text{Spur gears}$$

$$d = \frac{N}{P_{nd} \cos \psi} \quad \text{Helical gears}$$

Where N is the total number of teeth, p is the circular pitch, P_d is the diametrical pitch, and ψ is the helix angle for helical gears.

Standard reference pitch diameter

The **standard reference pitch diameter** is the diameter of the standard pitch circle. In spur and helical gears, unless otherwise specified, the standard pitch diameter is related to the number of teeth and the standard transverse pitch. It is obtained as:

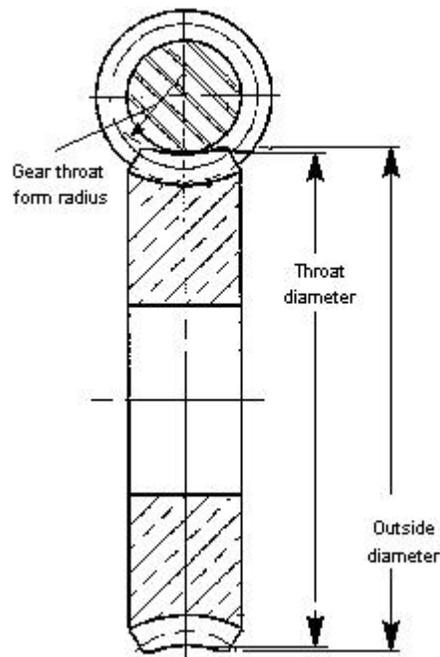
$$d = zm = \frac{zp}{\pi} = z \frac{m_n}{\cos \beta}$$

$$D = \frac{N}{P_d} = \frac{Np}{\pi} = \frac{N}{P_{nd} \cos \psi}$$

Test radius

The **test radius (R_r)** is a number used as an arithmetic convention established to simplify the determination of the proper test distance between a master and a work gear for a composite action test. It is used as a measure of the effective size of a gear. The test radius of the master, plus the test radius of the work gear is the set up center distance on a composite action test device. Test radius is not the same as the operating pitch radii of two tightly meshing gears unless both are perfect and to basic or standard tooth thickness.

Throat diameter



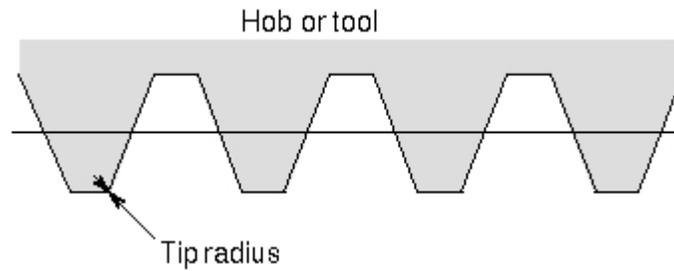
Wormgear diameters

The **throat diameter** is the diameter of the addendum circle at the central plane of a wormgear or of a double-enveloping wormgear.

Throat form radius

Throat form radius is the radius of the throat of an enveloping wormgear or of a double-enveloping worm, in an axial plane.

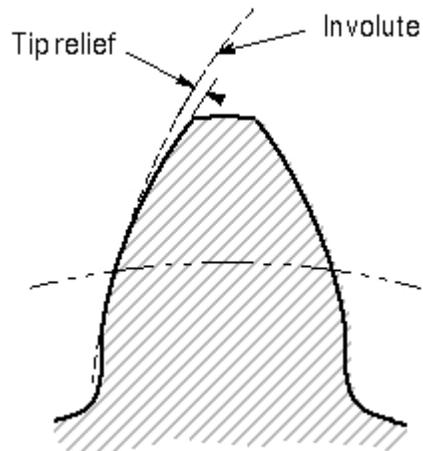
Tip radius



Tip radius

Tip radius is the radius of the circular arc used to join a side-cutting edge and an end-cutting edge in gear cutting tools. Edge radius is an alternate term.

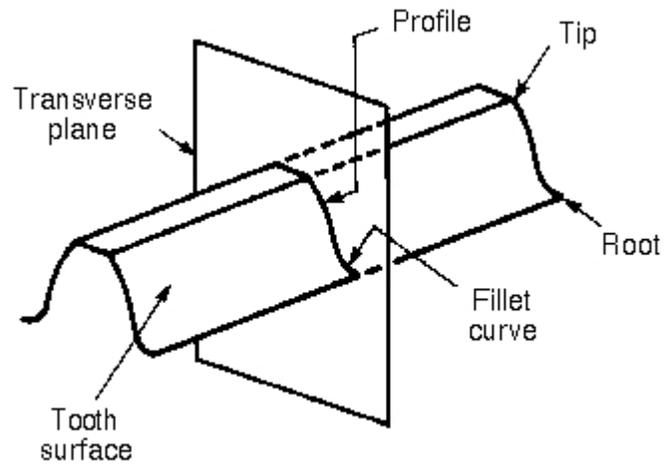
Tip relief



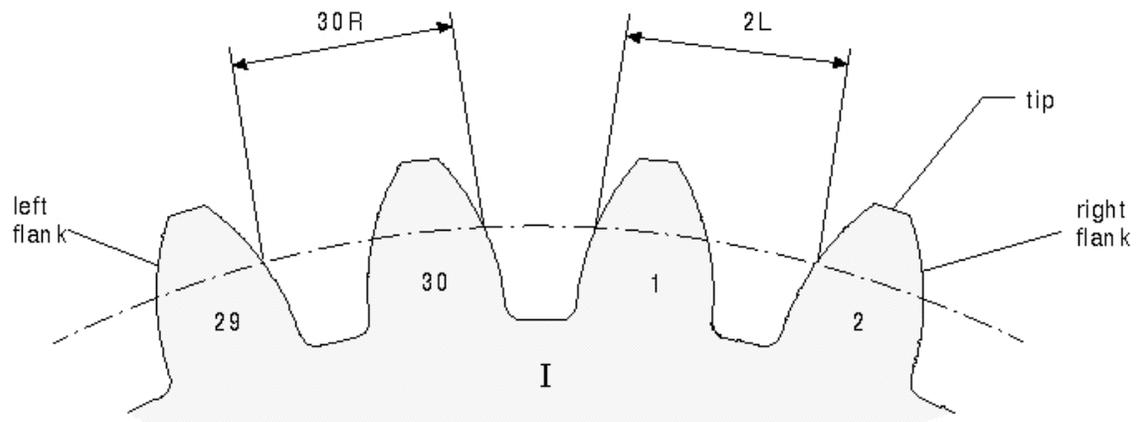
Tip relief

Tip relief is a modification of a tooth profile whereby a small amount of material is removed near the tip of the gear tooth.

Tooth surface

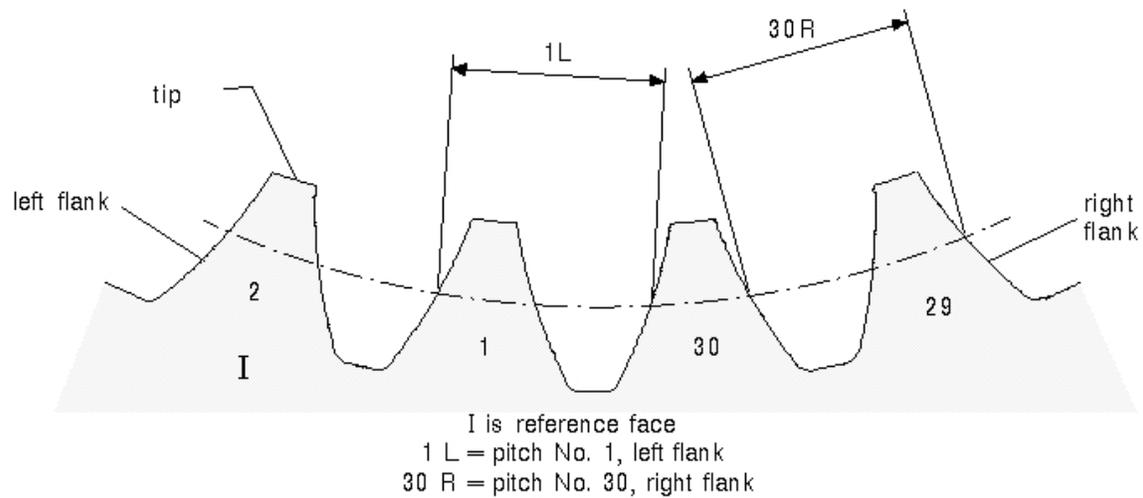


Profile of a spur gear



I is reference face
30 R = pitch No. 30, right flank
2 L = pitch No. 2, left flank

Notation and numbering for an external gear



Notation and numbering for an internal gear

The **tooth surface** (flank) forms the side of a gear tooth.

It is convenient to choose one face of the gear as the reference face and to mark it with the letter “I”. The other non-reference face might be termed face “II”.

For an observer looking at the reference face, so that the tooth is seen with its tip uppermost, the right flank is on the right and the left flank is on the left. Right and left flanks are denoted by the letters “R” and “L” respectively.