Mechanical Power Transmission

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First Edition, 2012

ISBN 978-81-323-3081-3

Published by:
Research World
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

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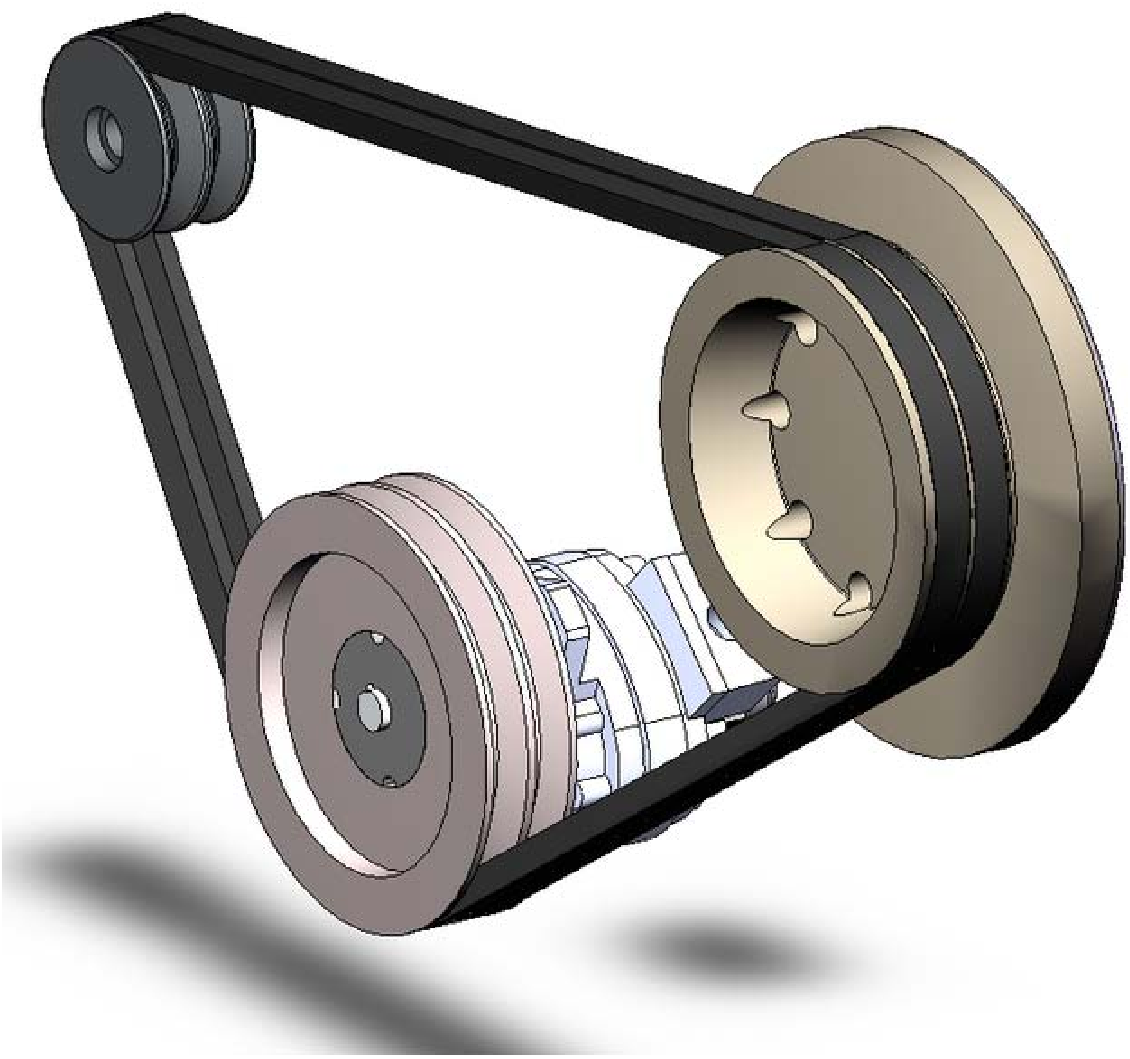
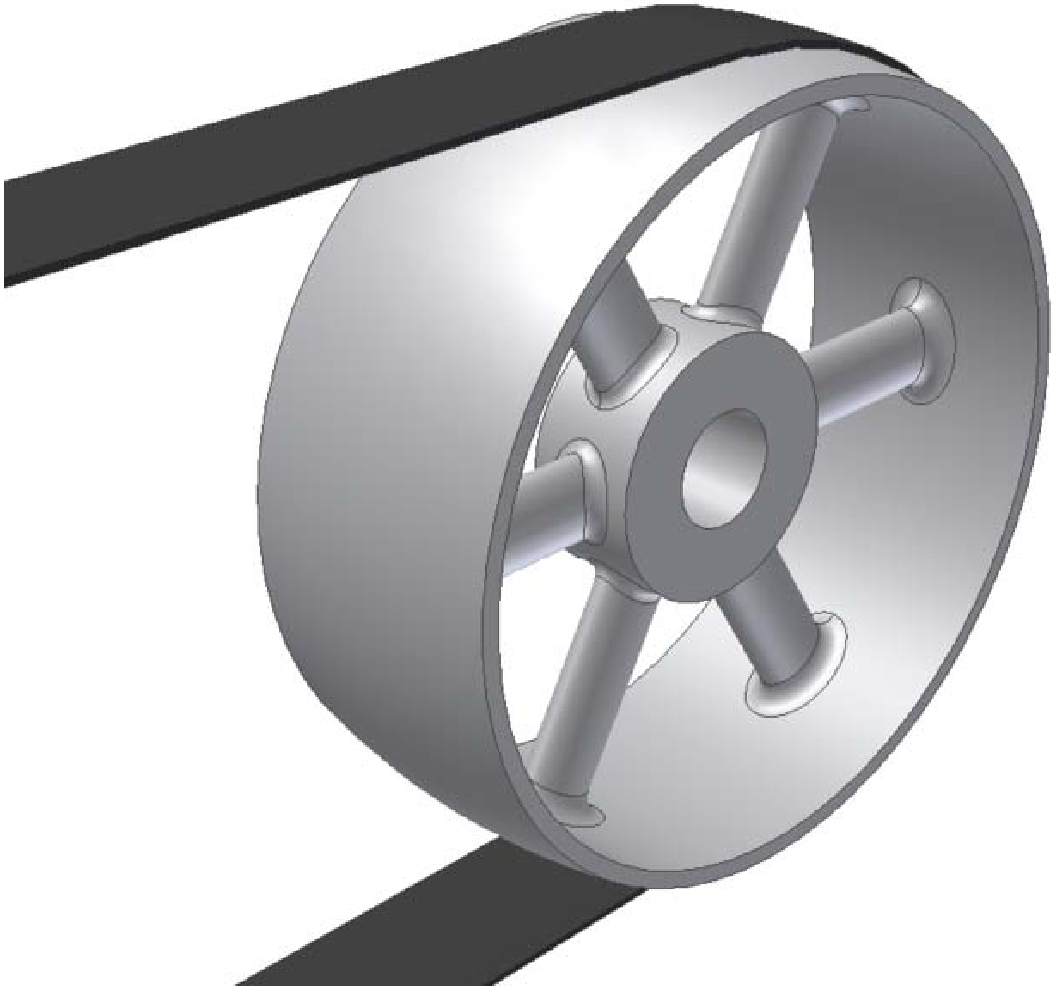
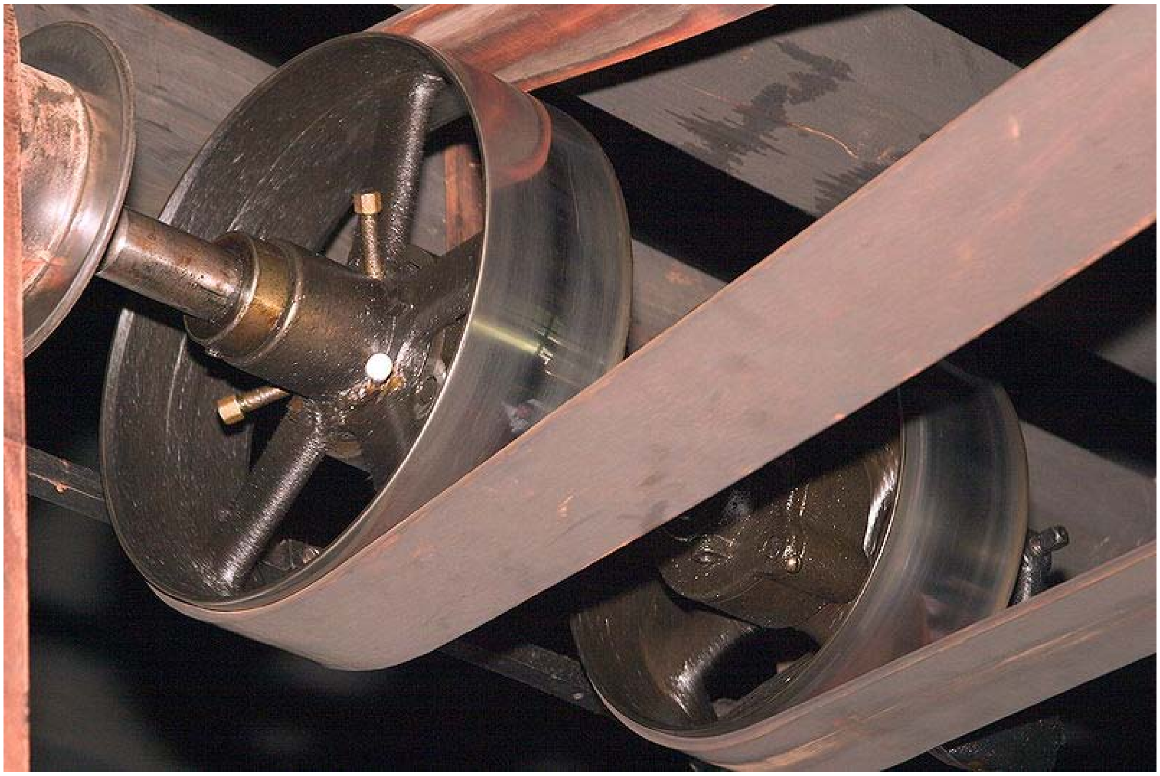
Belt (Mechanical)



A pair of vee-belts



flat belt



Flat belt drive in the machine shop at the Hagley Museum

A **belt** is a loop of flexible material used to link two or more rotating shafts mechanically. Belts may be used as a source of motion, to transmit power efficiently, or to track relative movement. Belts are looped over pulleys. In a two pulley system, the belt can either drive the pulleys in the same direction, or the belt may be crossed, so that the direction of the shafts is opposite. As a source of motion, a conveyor belt is one application where the belt is adapted to continually carry a load between two points.

Power transmission

Belts are the cheapest utility for power transmission between shafts that may not be axially aligned. Power transmission is achieved by specially designed belts and pulleys. The demands on a belt drive transmission system are large and this has led to many variations on the theme. They run smoothly and with little noise, and cushion motor and bearings against load changes, albeit with less strength than gears or chains. However, improvements in belt engineering allow use of belts in systems that only formerly allowed chains or gears.

Pros and cons

Belt drive, moreover, is simple, inexpensive, and does not require axially aligned shafts. It helps protect the machinery from overload and jam, and damps and isolates noise and vibration. Load fluctuations are shock-absorbed (cushioned). They need no lubrication and minimal maintenance. They have high efficiency (90-98%, usually 95%), high tolerance for misalignment, and are inexpensive if the shafts are far apart. Clutch action is activated by releasing belt tension. Different speeds can be obtained by step or tapered pulleys.

The angular-velocity ratio may not be constant or equal to that of the pulley diameters, due to slip and stretch. However, this problem has been largely solved by the use of toothed belts. Temperatures ranges from −31 °F (−35 °C) to 185 °F (85 °C). Adjustment of center distance or addition of an idler pulley is crucial to compensate for wear and stretch.

Flat belts

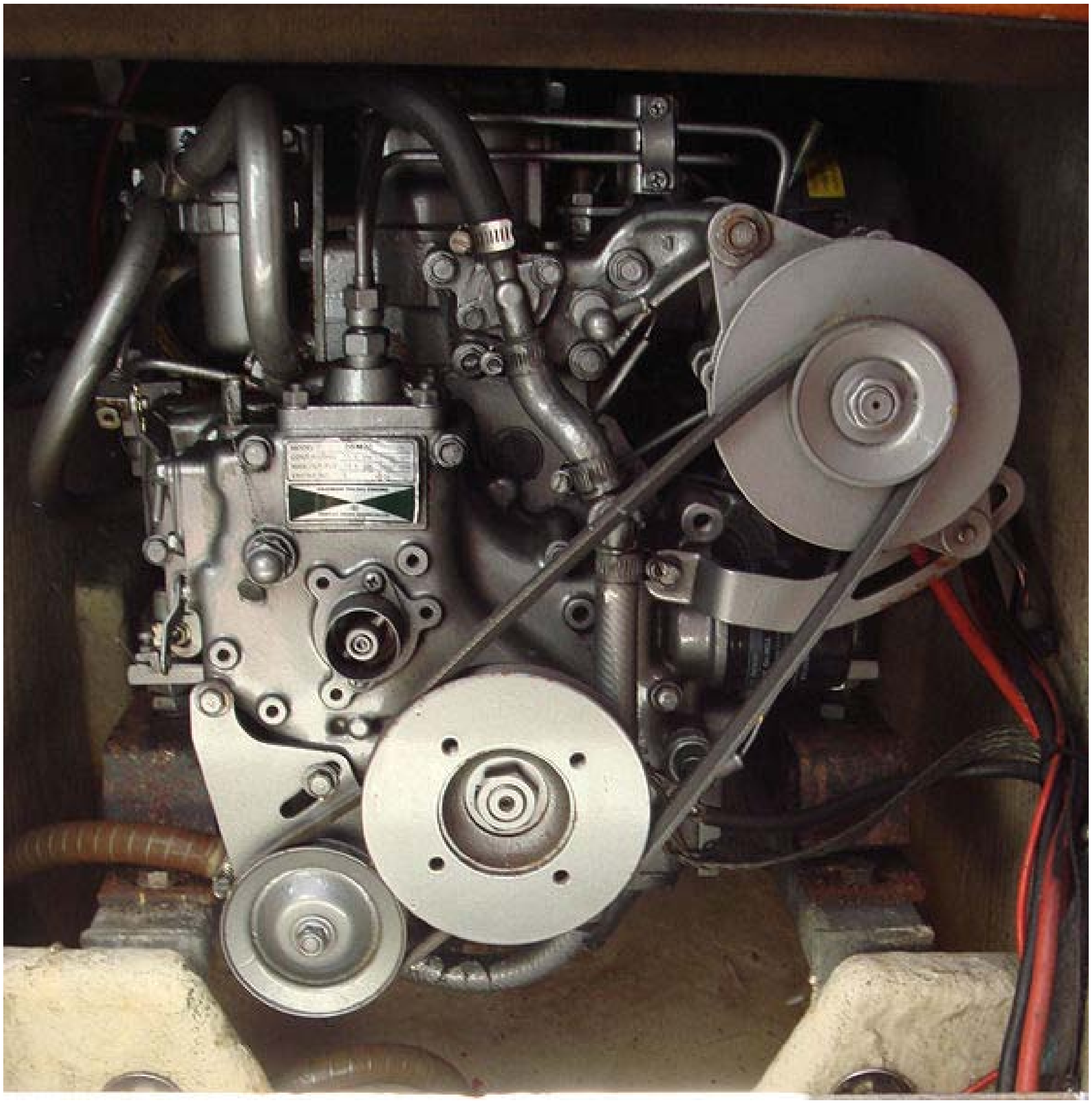
The drive belt: used to transfer power from the engine's flywheel. Here shown driving a threshing machine.

Flat belts were used early in line shafting to transmit power in factories. They were also used in countless farming, mining, and logging applications, such as bucksaws, sawmills, threshers, silo blowers, conveyors for filling corn cribs or haylofts, balers, water pumps (for wells, mines, or swampy farm fields), and electrical generators. The flat belt is a simple system of power transmission that was well suited for its day. It delivered high power for high speeds (500 hp for 10,000 ft/min), in cases of wide belts and large pulleys. These drives are bulky, requiring high tension leading to high loads, so vee belts have mainly replaced the flat-belts except when high speed is needed over power. The Industrial Revolution soon demanded more from the system, and flat belt pulleys needed to be carefully aligned to prevent the belt from slipping off. Because flat belts tend to climb towards the higher side of the pulley, pulleys were made with a slightly convex or "crowned" surface (rather than flat) to keep the belts centered. Flat belts also tend to slip on the pulley face when heavy loads are applied and many proprietary dressings were available that could be applied to the belts to increase friction, and so power transmission. Grip was better if the belt was assembled with the hair (i.e. outer) side of the leather against the pulley although belts were also often given a half-twist before joining the ends (forming a Möbius strip), so that wear was evenly distributed on both sides of the belt (DB). Belts were joined by lacing the ends together with leather thonging, or later by steel comb fasteners. A good modern use for a flat belt is with smaller pulleys and large central distances. They can connect inside and outside pulleys, and can come in both endless and jointed construction.

Round belts

Round belts are a circular cross section belt designed to run in a pulley with a circular (or near circular) groove. They are for use in low torque situations and may be purchased in various lengths or cut to length and joined, either by a staple, gluing or welding (in the case of polyurethane). Early sewing machines utilized a leather belt, joined either by a metal staple or glued, to a great effect.

Vee belts



Belts on a Yanmar 2GM20 marine diesel engine.

A multiple-V-belt drive on an air compressor.

Vee belts (also known as V-belt or wedge rope) solved the slippage and alignment problem. It is now the basic belt for power transmission. They provide the best combination of traction, speed of movement, load of the bearings, and long service life. The V-belt was developed in 1917 by John Gates of the Gates Rubber Company. They are generally endless, and their general cross-section shape is trapezoidal. The "V" shape of the belt tracks in a mating groove in the pulley (or sheave), with the result that the belt cannot slip off. The belt also tends to wedge into the groove as the load increases — the greater the load, the greater the wedging action — improving torque transmission and making the V-belt an effective solution, needing less width and tension than flat belts. V-belts trump flat belts with their small center distances and high reduction ratios. The preferred center distance is larger than the largest pulley diameter, but less than three times the sum of both pulleys. Optimal speed range is 1000–7000 ft/min. V-belts need larger pulleys for their larger thickness than flat belts. They can be supplied at various fixed lengths or as a segmented section, where the segments are linked (spliced) to form a belt of the required length. For high-power requirements, two or more vee belts can be joined side-by-side in an arrangement called a multi-V, running on matching multi-groove sheaves. The strength of these belts is obtained by reinforcements with fibers like steel, polyester or aramid (e.g. Twaron or Kevlar). This is known as a multiple-V-belt drive (or sometimes a "classical V-belt drive"). When an endless belt does not fit the need, jointed and link V-belts may be employed. However they are weaker and only usable at speeds up to 4000 ft/min. A link v-belt is a number of rubberized fabric links held together by metal fasteners. They are length adjustable by disassembling and removing links when needed.

Multi-groove belts

A multi-groove or polygroove belt is made up of usually 5 or 6 "V" shapes along side each other. This gives a thinner belt for the same drive surface, thus is more flexible, although often wider. The added flexibility offers an improved efficiency, as less energy is wasted in the internal friction of continually bending the belt. In practice this gain of efficiency is overshadowed by the reduced heating effect on the belt, as a cooler-running belt lasts longer in service.

A further advantage of the polygroove belt, and the reason they have become so popular, stems from the ability to be run over pulleys on the ungrooved back of the belt. Although this is sometimes done with vee belts and a single idler pulley for tensioning, a polygroove belt may be wrapped around a pulley on its back tightly enough to change its direction, or even to provide a light driving force.

Any vee belt's ability to drive pulleys depends on wrapping the belt around a sufficient angle of the pulley to provide grip. Where a single-vee belt is limited to a simple convex shape, it can adequately wrap at most three or possibly four pulleys, so can drive at most three accessories. Where more must be driven, such as for modern cars with power steering and air conditioning, multiple belts are required. As the polygroove belt can be bent into concave paths by external idlers, it can wrap any number of driven pulleys, limited only by the power capacity of the belt.

This ability to bend the belt at the designer's whim allows it to take a complex or "serpentine" path. This can assist the design of a compact engine layout, where the accessories are mounted more closely to the engine block and without the need to provide movable tensioning adjustments. The entire belt may be tensioned by a single idler pulley.

Ribbed belt

A ribbed belt is a power transmission belt featuring lengthwise grooves. It operates from contact between the ribs of the belt and the grooves in the pulley. Its single-piece structure it reported to offer an even distribution of tension across the width of the pulley where the belt is in contact, a power range up to 600 kW, a high speed ratio, serpentine drives (possibility to drive off the back of the belt), long life, stability and homogeneity of the drive tension, and reduced vibration. The ribbed belt may be fitted on various applications : compressors, fitness bikes, agricultural machinery, food mixers, washing machines, lawn mowers, etc.

Film belts

Though often grouped with flat belts, they are actually a different kind. They consist of a very thin belt (0.5-15 millimeters or 100-4000 micrometres) strip of plastic and occasionally rubber. They are generally intended for low-power (10 hp or 7 kW), high-speed uses, allowing high efficiency (up to 98%) and long life. These are seen in business machines, printers, tape recorders, and other light-duty operations.

Timing belts

Timing belt

Belt-drive cog on a belt-driven bicycle

Timing belts, (also known as **Toothed**, **Notch**, **Cog**, or **Synchronous** belts) are a *positive* transfer belt and can track relative movement. These belts have teeth that fit into a matching toothed pulley. When correctly tensioned, they have no slippage, run at constant speed, and are often used to transfer direct motion for indexing or timing purposes (hence their name). They are often used in lieu of chains or gears, so there is less noise and a lubrication bath is not necessary. Camshafts of automobiles, miniature timing systems, and stepper motors often utilize these belts. Timing belts need the least tension of all belts, and are among the most efficient. They can bear up to 200 hp (150 kW) at speeds of 16,000 ft/min.

Timing belts with a helical offset tooth design are available. The helical offset tooth design forms a chevron pattern and causes the teeth to engage progressively. The chevron pattern design is self-aligning. The chevron pattern design does not make the noise that some timing belts make at idiosyncratic speeds, and is more efficient at transferring power (up to 98%).

Disadvantages include a relatively high purchase cost, the need for specially fabricated toothed pulleys, less protection from overloading and jamming, and the lack of clutch action.

Specialty belts

Belts normally transmit power on the tension side of the loop. However, designs for continuously variable transmissions exist that use belts that are a series of solid metal blocks, linked together as in a chain, transmitting power on the compression side of the loop.

Rolling roads

Belts used for rolling roads for wind tunnels can be capable of 250 km/h.

Flying rope

For transmission of mechanical power over distance without electrical energy, a flying rope can be used. A wire or manila rope can be used to transmit mechanical energy from a steam engine or water wheel to a factory or pump which is located a considerable distance (10 to 100s of meters or more) from the power source. A flying rope way could be supported on poles and pulleys similar to the cable on a chair lift or aerial tramway. Transmission efficiency is generally high.

Standards for use

The open belt drive has parallel shafts rotating in the same direction, whereas the cross-belt drive also bears parallel shafts but rotate in opposite direction. The former is far more common, and the latter not appropriate for timing and standard V-belts, because the pulleys contact both the both inner and outer belt surfaces. Nonparallel shafts can be connected if the belt's center line is aligned with the center plane of the pulley. Industrial belts are usually reinforced rubber but sometimes leather types, non-leather non-reinforced belts, can only be used in light applications.

The pitch line is the line between the inner and outer surfaces that is neither subject to tension (like the outer surface) nor compression (like the inner). It is midway through the surfaces in film and flat belts and dependent on cross-sectional shape and size in timing and V-belts. The angular speed is inversely proportional to size, so the larger the one wheel, the less angular velocity, and vice versa. Actual pulley speeds tend to be 0.5–1% less than generally calculated because of belt slip and stretch. In timing belts, the inverse ratio teeth of the belt contributes to the exact measurement. The speed of the belt is:

Speed = Circumference based on pitch diameter × angular speed in rpm

Selection criteria

Belt drives are built under the following required conditions: speeds of and power transmitted between drive and driven unit; suitable distance between shafts; and appropriate operating conditions. The equation for power is:

power (kW) = (torque in newton-meters) × (rpm) × (2π radians)/(60 sec × 1000 W)

Factors of power adjustment include speed ratio; shaft distance (long or short); type of drive unit (electric motor, internal combustion engine); service environment (oily, wet, dusty); driven unit loads (jerky, shock, reversed); and pulley-belt arrangement (open, crossed, turned). These are found in engineering handbooks and manufacturer's literature. When corrected, the horsepower is compared to rated horsepowers of the standard belt cross sections at particular belt speeds to find a number of arrays that will perform best. Now the pulley diameters are chosen. It is generally either large diameters or large cross section that are chosen, since, as stated earlier, larger belts transmit this same power at low belt speeds as smaller belts do at high speeds. To keep the driving part at its smallest, minimum-diameter pulleys are desired. Minimum pulley diameters are limited by the elongation of the belt's outer fibers as the belt wraps around the pulleys. Small pulleys increase this elongation, greatly reducing belt life. Minimum pulley diameters are often listed with each cross section and speed, or listed separately by belt cross section. After the cheapest diameters and belt section are chosen, the belt length is computed. If endless belts are used, the desired shaft spacing may need adjusting to accommodate standard length belts. It is often more economical to use two or more juxtaposed V-belts, rather than one larger belt.

In large speed ratios or small central distances, the angle of contact between the belt and pulley may be less than 180°. If this is the case, the drive power must be further increased, according to manufacturer's tables, and the selection process repeated. This is because power capacities are based on the standard of a 180° contact angle. Smaller contact angles mean less area for the belt to obtain traction, and thus the belt carries less power.

Belt friction

Belt drives depend on friction to operate but, if the friction is excessive, there will be waste of energy and rapid wear of the belt. Factors which affect belt friction include belt tension, contact angle and the materials from which the belt and pulleys are made.

Belt tension

Power transmission is a function of belt tension. However, also increasing with tension is stress (load) on the belt and bearings. The ideal belt is that of the lowest tension which does not slip in high loads. Belt tensions should also be adjusted to belt type, size, speed, and pulley diameters. Belt tension is determined by measuring the force to deflect the belt a given distance per inch of pulley. Timing belts need only adequate tension to keep the belt in contact with the pulley.

Belt wear

Fatigue, more so than abrasion, is the culprit for most belt problems. This wear is caused by stress from rolling around the pulleys. High belt tension; excessive slippage; adverse environmental conditions; and belt overloads caused by shock, vibration, or belt slapping all contribute to belt fatigue.

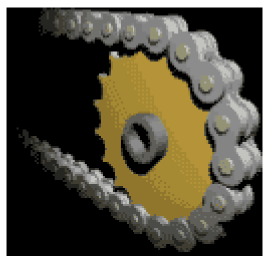
Specifications

To fully specify a belt, the material, length, and cross-section size and shape are required. Timing belts, in addition, require that the size of the teeth be given. The length of the belt is the sum of the central length of the system on both sides, half the circumference of both pulleys, and the square of the sum (if crossed) or the difference (if open) of the radii. Thus, when dividing by the central distance, it can be visualized as the central distance times the height that gives the same squared value of the radius difference on, of course, both sides. When adding to the length of either side, the length of the belt increases, in a similar manner to the Pythagorean theorem. One important concept to remember is that as D_1 gets closer to D_2 there is less of a distance (and therefore less addition of length) until its approaches zero.

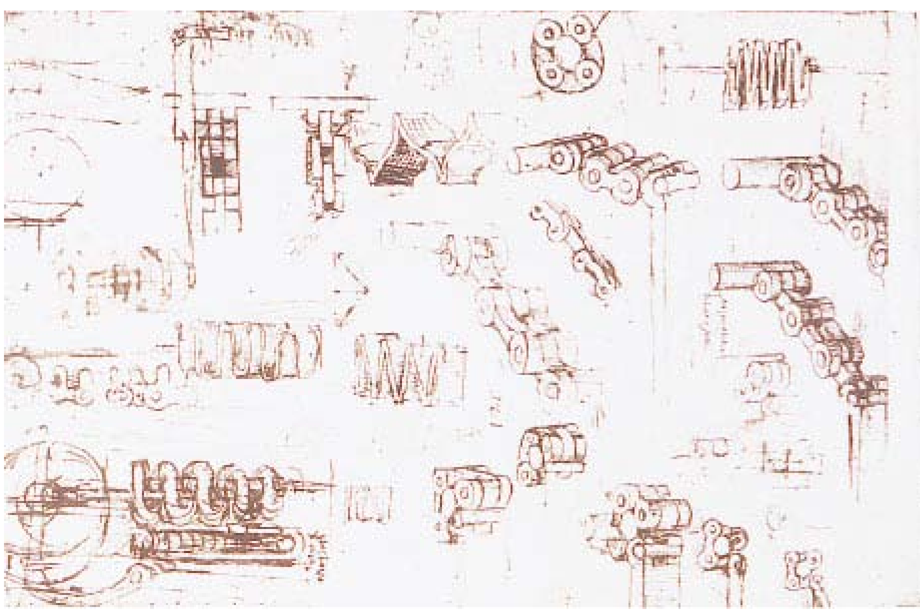
On the other hand, in a crossed belt drive the *sum* rather than the difference of radii is the basis for computation for length. So the wider the small drive increases, the belt length is higher.

Chapter 2

Roller Chain



Roller chain and sprocket



The sketch of roller chain, Leonardo da Vinci

Roller chain or **bush roller chain** is the type of chain most commonly used for transmission of mechanical power on many kinds of domestic, industrial and agricultural machinery, including conveyors, wire and tube drawing machines, printing presses, cars, motorcycles, and simple machines like bicycles. It is a simple, reliable, and efficient means of power transmission.

Though Hans Renold is credited with inventing roller chain in 1880, sketches by Leonardo da Vinci in the 16th century show a chain with a roller bearing.

Construction of the chain

There are actually two types of links alternating in the bush roller chain. The first type is inner links, having two inner plates held together by two sleeves or bushings upon which rotate two rollers. Inner links alternate with the second type, the outer links, consisting of two outer plates held together by pins passing through the bushings of the inner links. The "bushingless" roller chain is similar in operation though not in construction; instead of separate bushings or sleeves holding the inner plates together, the plate has a tube stamped into it protruding from the hole which serves the same purpose. This has the advantage of removing one step in assembly of the chain.

The roller chain design reduces friction compared to simpler designs, resulting in higher efficiency and less wear. The original power transmission chain varieties lacked rollers and bushings, with both the inner and outer plates held by pins which directly contacted the sprocket teeth; however this configuration exhibited extremely rapid wear of both the sprocket teeth, and the plates where they pivoted on the pins. This problem was partially solved by the development of bushed chains, with the pins holding the outer plates passing through bushings or sleeves connecting the inner plates. This distributed the wear over a greater area; however the teeth of the sprockets still wore more rapidly than is desirable, from the sliding friction against the bushings. The addition of rollers surrounding the bushing sleeves of the chain and provided rolling contact with the teeth of the sprockets resulting in excellent resistance to wear of both sprockets and chain as well. There is even very low friction, as long as the chain is sufficiently lubricated. Continuous, clean, lubrication of roller chains is of primary importance for efficient operation.

Lubrication

The great majority of driving chains operate in clean environments, the wearing surfaces (ie the pins and the bushings) safe from precipitation and air-born grit, many even in a sealed environment such as an oil bath.

A few other chains run unprotected and in those cases, internally sealed roller chain manufacturers such as Tsubaki, Diamond, Morse, Renold, and Rexnord produce low-maintenance versions wherein o-rings or x-rings seal in the lubricant for life.

However, there are a few chains that have to operate in dirty conditions, and for size or operational reasons cannot be sealed. One example is the bicycle chain drive on a derailleur equipped bicycle (though cheaper hub-gear bicycles may be similarly naked to the elements). These chains will necessarily have relatively high rates of wear, particularly when the operators are prepared to accept more friction, less efficiency, more noise and more frequent replacement as they neglect lubrication and adjustment.

Motorcycle chain lubrication

Chains operating at high speeds comparable to those on motorcycles should be used in conjunction with an oil bath. For modern motorcycles this is not applicable and most motorcycle chains run unprotected. They are subject to extreme forces and have to operate in tough conditions being exposed to rain, dirt, sand and road salt.

Motorcycle chains are part of the drive train to transmit the motor power to the back wheel. While properly lubricated chains can reach an efficiency of more 98% in the transmission, unlubricated chains will significantly decrease performance and increase chain and sprockets wear.

Two distinct types of aftermarket lubricants are available for motorcycle chains, spray on lubricants and oil drip feed systems.

- Spray lubricants may contain wax or PTFE. Whilst these lubricants use tack additives to stay on the chain they can also attract dirt and sand from the road and over time produce a grinding paste that accelerates component wear.
- Oil drip feed systems continuously lubricate the chain and use light oil that does not stick to the chain. Research has shown that oil drip feed systems provide the greatest wear protection and greatest power saving .

Scottoiler

Oil drip feed systems or **automatic motorcycle chain oilers** are often referred to as ‘Scottoilers’. Scottoiler Ltd. is a manufacturer of automatic oil drip feed systems for motorbikes. The original product is based on a vacuum system and works by gravity feed. The engine vacuum provides the power to open a valve. The oil then siphons from the reservoir by gravity and the flow rate can be adjusted by a dial opening/closing the valve aperture.

Especially in the UK the brand is on the way to become a genericized trademark.

Variants in design

If the chain is not being used for a high wear application (for instance if it is just transmitting motion from a hand operated lever to a control shaft on a machine, or a sliding door on an oven), then one of the simpler types of chain may still be used. Conversely, where extra strength but the smooth drive of a smaller pitch is required, the chain may be "siamesed"; instead of just two rows of plates on the outer sides of the chain, there may be three ("duplex"), four ("triplex"), or more rows of plates running parallel, with bushings and rollers between each adjacent pair, and the same number of rows of teeth running in parallel on the sprockets to match. Timing chains on automotive engines, for example, typically have multiple rows of plates called strands.

Roller chain is made in several sizes, the most common American National Standards Institute (ANSI) standards being 40, 50, 60, and 80. The first digit(s) indicate the pitch of the chain in eighths of an inch, with the last digit being 0 for standard chain, 1 for lightweight chain, and 5 for bushed chain with no rollers. Thus, a bicycle chain with half inch pitch would be a #40 while a #160 sprocket would have teeth spaced 2 inches apart, etc. Metric pitches are expressed in sixteenths of an inch; thus a metric #8 chain (08B-1) would be equivalent to an ANSI #40. Most roller chain is made from plain carbon or alloy steel, but stainless steel is used in food processing machinery or other places where lubrication is a problem, and nylon or brass are occasionally seen for the same reason.

Roller chain is ordinarily hooked up using a master link (also known as a connecting link), which typically has one pin held by a horseshoe clip rather than friction fit, allowing it to be inserted or removed with simple tools. Half links (also known as offsets) are available and are used to increase the length of the chain by a single roller.

Use

- Roller chains are used in low- to mid-speed drives at around 600 to 800 feet per minute; however, at higher speeds, around 2,000 to 3,000 feet per minute, V-belts are normally used due to wear and noise issues.

- A bicycle chain is a form of roller chain. Bicycle chains may have a master link, or may require a chain tool for removal and installation. A similar but larger and thus stronger chain is used on most motorcycles although it is sometimes replaced by either a toothed belt or a shaft drive, which offer lower noise level and fewer maintenance requirements.

- In older automobile engines from the United States and other countries, roller chains would traditionally drive the camshaft(s) off the crankshaft, generating less noise than a gear drive as used in very high performance engines, and offering more durability than the timing belt frequently used on more modern engines. Many modern automobile engines still use roller chains, which are more durable than timing belts.

- Chains are also used in forklifts using hydraulic rams as a pulley to raise and lower the carriage; however, these chains are not considered roller chains, but are classified as lift or leaf chains.

- Chainsaw cutting chains superficially resemble roller chains but are more closely related to leaf chains. They are driven by projecting drive links which also serve to locate the chain onto the bar.

Sea Harrier FA.2 *ZA195* front (cold) vector thrust nozzle - the nozzle is rotated by a chain drive from an air motor

- A perhaps unusual use of a pair of motorcycle chains is in the Harrier Jump Jet, where a chain drive from an air motor is used to rotate the movable engine nozzles, allowing them to be pointed downwards for hovering flight, or to the the rear for normal forward flight, a system known as Thrust vectoring.

Wear

The effect of wear on a roller chain is to increase the pitch (spacing of the links), causing the chain to grow longer. Note that this is due to wear at the pivoting pins and bushes, not from actual stretching of the metal (as does happen to some flexible steel components such as the hand-brake cable of a motor vehicle).

With modern chains it is unusual for a chain (other than that of a bicycle) to wear until it breaks, since a worn chain leads to the rapid onset of wear on the teeth of the sprockets, with ultimate failure being the loss of all the teeth on the sprocket. The sprockets (in particular the larger of the two) suffer a grinding motion that puts a characteristic hook shape into the driven face of the teeth. (This effect is made worse by a chain improperly tensioned, but is unavoidable no matter what care is taken). The worn teeth (and chain) no longer provides smooth transmission of power and this may become evident from the noise, the vibration or (in car engines using a timing chain) the variation in ignition timing seen with a timing light. Both sprockets and chain should be replaced in these cases, since a new chain on worn sprockets will not last long. However, in less severe cases it may be possible to save the smaller of the two sprockets, since it is always the larger one that suffers the most wear. Only in very light-weight applications such as a bicycle, or in extreme cases of improper tension, will the chain normally jump off the sprockets.

The lengthening due to wear of a chain is calculated by the following formula:

$\% = ((M - (S * P)) / (S * P)) * 100$

M = the length of a number of links measured

S = the number of links measured

P = Pitch

In industry, it is usual to monitor the movement of the chain tensioner (whether manual or automatic) or the exact length of a drive chain (one rule of thumb is to replace a roller chain which has elongated 3% on an adjustable drive or 1.5% on a fixed-center drive). A simpler method, particularly suitable for the cycle or motorcycle user, is to attempt to pull the chain away from the larger of the two sprockets. Any significant movement (eg making it possible to see through a gap) probably indicates a chain worn up to and beyond the limit. Sprocket damage will result if the problem is ignored.

Bicycle chain wear

The lightweight chain of a bicycle with derailleur gears can snap (or rather, come apart at the side-plates, since it is normal for the riveting to fail first) because the wearing pins inside are not parallel, they are barrel-shaped. Contact between the pin and the bush is not the regular line, but a point. This form of construction is necessary because the gear-changing action of this form of transmission requires the chain to both bend sideways and to twist.

Chain failure is much less of a problem on hub-geared systems (often known as "Sturmey Archer") since the parallel pins have a much bigger wearing surface in contact with the bush. The hub-gear system also allows complete enclosure, a great aid to lubrication and protection from grit.

Chain strength

The most common measure of roller chain's strength is tensile strength. Tensile strength represents how much load a chain can withstand under a one-time load before breaking.

Just as important as tensile strength is a chain's fatigue strength. The critical factors in a chain's fatigue strength is the quality of steel used to manufacture the chain, the heat treatment of the chain components, the quality of the pitch hole fabrication of the linkplates, and the type of shot plus the intensity of shot peen coverage on the linkplates. Other factors can include the thickness of the linkplates and the design (contour) of the linkplates. The rule of thumb for roller chain operating on a continuous drive is for the chain load to not exceed a mere 1/6 or 1/9 of the chain's tensile strength, depending on the type of master links used (press-fit vs. slip-fit). Roller chains operating on a continuous drive beyond these thresholds can and typically do fail prematurely via linkplate fatigue failure.

The standard minimum ultimate strength of the ANSI 29.1 steel chain is 12,500 x (pitch, in inches)^2 (pitch squared x 12,500).

Chain standards

Standards organizations (such as ANSI) maintain standards for design, dimensions, and interchangeability of transmission chains. For example, the following table shows the principal data of ANSI standard B29.1 (Precision Power Transmission Roller Chains, Attachments, and Sprockets).

> NOTE: As of 1 January 2002, ANSI/AMSE B29.1 has been incorporated into ASME B29.100.

ANSI B29.1 roller chain standard sizes				
Size	**Pitch**	**Roller diameter**	**Tensile strength**	**Working load**
25	0.250 in (6.35 mm)	0.130 in (3.30 mm)	781 lb (354 kg)	140 lb (64 kg)
35	0.375 in (9.53 mm)	0.200 in (5.08 mm)	1,758 lb (797 kg)	480 lb (220 kg)
41	0.500 in (12.70 mm)	0.306 in (7.77 mm)	1,500 lb (680 kg)	500 lb (230 kg)
40	0.500 in (12.70 mm)	0.312 in (7.92 mm)	3,125 lb (1,417 kg)	810 lb (370 kg)
50	0.625 in (15.88 mm)	0.400 in (10.16 mm)	4,880 lb (2,210 kg)	1,430 lb (650 kg)
60	0.750 in (19.05 mm)	0.469 in (11.91 mm)	7,030 lb (3,190 kg)	1,980 lb (900 kg)
80	1.000 in (25.40 mm)	0.625 in (15.88 mm)	12,500 lb (5,700 kg)	3,300 lb (1,500 kg)
100	1.250 in (31.75	0.750 in (19.05	19,531 lb (8,859 kg)	5,072 lb (2,301 kg)

	mm)	mm)		
120	1.500 in (38.10 mm)	0.875 in (22.23 mm)	28,100 lb (12,700 kg)	6,800 lb (3,100 kg)
140	1.750 in (44.45 mm)	1.000 in (25.40 mm)	38,280 lb (17,360 kg)	9,040 lb (4,100 kg)
160	2.000 in (50.80 mm)	1.125 in (28.58 mm)	50,000 lb (23,000 kg)	11,900 lb (5,400 kg)
180	2.250 in (57.15 mm)	1.460 in (37.08 mm)	63,300 lb (28,700 kg)	13,700 lb (6,200 kg)
200	2.500 in (63.50 mm)	1.562 in (39.67 mm)	78,000 lb (35,000 kg)	16,000 lb (7,300 kg)
240	3.000 in (76.20 mm)	1.875 in (47.63 mm)	112,500 lb (51,000 kg)	22,250 lb (10,090 kg)

For mnemonic purposes, below is another presentation of key dimensions from the same standard, expressed in fractions of an inch (which was part of the thinking behind the choice of preferred numbers in the ANSI standard):

Pitch (inches)	Pitch expressed in eighths	ANSI standard chain number	Width (inches)
1⁄4	**2**⁄8	**2**5	1⁄8
3⁄8	**3**⁄8	**3**5	3⁄16
1⁄2	**4**⁄8	**4**1	1⁄4
1⁄2	**4**⁄8	**4**0	5⁄16
5⁄8	**5**⁄8	**5**0	3⁄8
3⁄4	**6**⁄8	**6**0	1⁄2
1	**8**⁄8	**8**0	5⁄8

Notes:
1. The pitch is the distance between roller centers. The width is the distance between the link plates (ie slightly more than the roller width to allow for clearance).
2. The right-hand digit of the standard denotes 0 = normal chain, 1 = lightweight chain, 5 = rollerless bushing chain.
3. The left-hand digit denotes the number of eighths

of an inch that make up the pitch. 4. An "H" following the standard number denotes heavyweight chain. A hyphenated number following the standard number denotes double-strand (2), triple-strand (3), and so on. Thus 60H-3 denotes number 60 heavyweight triple-strand chain.

A typical bicycle chain uses 40 series chain with a minimum tensile strength of 3,125 pounds (1,417 kg) and a working load of 810 lb (367 kg). The width of the chain is variable, and does not affect the load capacity.

Chapter 3

Variable-Frequency Drive

Small variable frequency drive

A **variable-frequency drive (VFD)** is a system for controlling the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electrical power supplied to the motor. A variable frequency drive is a specific type of adjustable-speed drive. Variable-frequency drives are also known as adjustable-frequency drives (AFD), variable-speed drives (VSD), AC drives, microdrives or inverter drives. Since the voltage is varied along with frequency, these are sometimes also called **VVVF** (variable voltage variable frequency) drives.

Variable-frequency drives are widely used. In ventilation systems for large buildings, variable-frequency motors on fans save energy by allowing the volume of air moved to match the system demand. They are also used on pumps, elevator, conveyor and machine tool drives.

VFD types

All VFDs use their output devices (IGBTs, transistors, thyristors) only as switches, turning them only on or off. Using a linear device such as a transistor in its linear mode is impractical for a VFD drive, since the power dissipated in the drive devices would be about as much as the power delivered to the load.

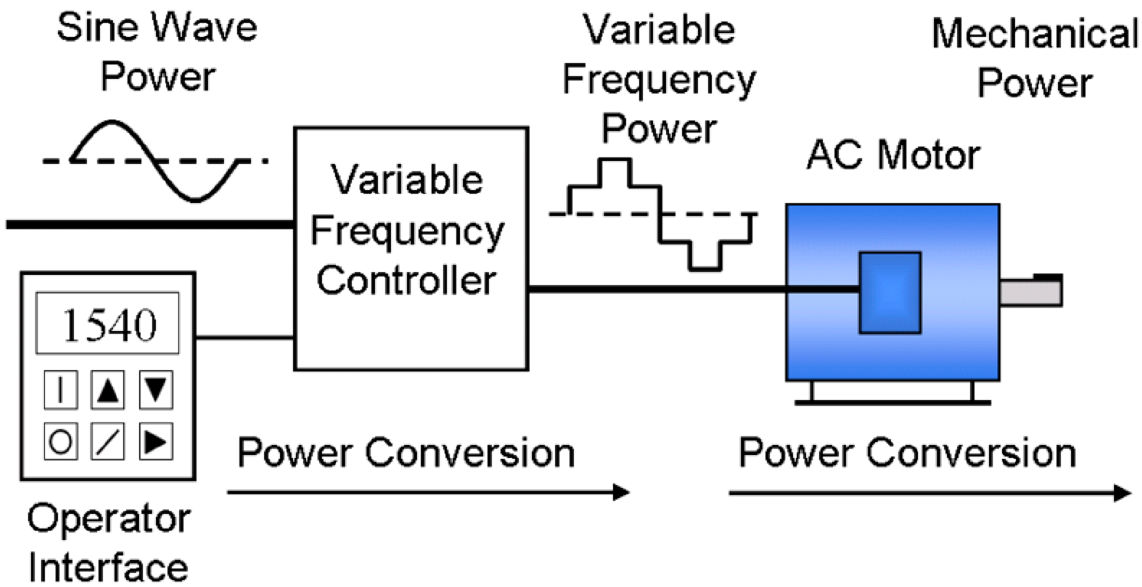
Drives can be classified as:

- Constant voltage
- Constant current
- Cycloconverter

In a constant voltage converter, the intermediate DC link voltage remains approximately constant during each output cycle. In constant current drives, a large inductor is placed between the input rectifier and the output bridge, so the current delivered is nearly constant. A cycloconverter has no input rectifier or DC link and instead connects each output terminal to the appropriate input phase.

The most common type of packaged VF drive is the constant-voltage type, using pulse width modulation to control both the frequency and effective voltage applied to the motor load.

VFD system description



VFD system

A variable frequency drive system generally consists of an AC motor, a controller and an operator interface.

VFD motor

The motor used in a VFD system is usually a three-phase induction motor. Some types of single-phase motors can be used, but three-phase motors are usually preferred. Various types of synchronous motors offer advantages in some situations, but induction motors are suitable for most purposes and are generally the most economical choice. Motors that are designed for fixed-speed operation are often used. Certain enhancements to the standard motor designs offer higher reliability and better VFD performance, such as MG-31 rated motors.

VFD controller

Variable frequency drive controllers are solid state electronic power conversion devices. The usual design first converts AC input power to DC intermediate power using a rectifier or converter bridge. The rectifier is usually a three-phase, full-wave-diode bridge. The DC intermediate power is then converted to quasi-sinusoidal AC power using an inverter switching circuit. The inverter circuit is probably the most important section of the VFD, changing DC energy into three channels of AC energy that can be used by an AC motor. These units provide improved power factor, less harmonic distortion, and low sensitivity to the incoming phase sequencing than older phase controlled converter VFD's. Since incoming power is converted to DC, many units will accept single-phase as well as three-phase input power (acting as a phase converter as well as a speed controller); however the unit must be derated when using single phase input as only part of the rectifier bridge is carrying the connected load.

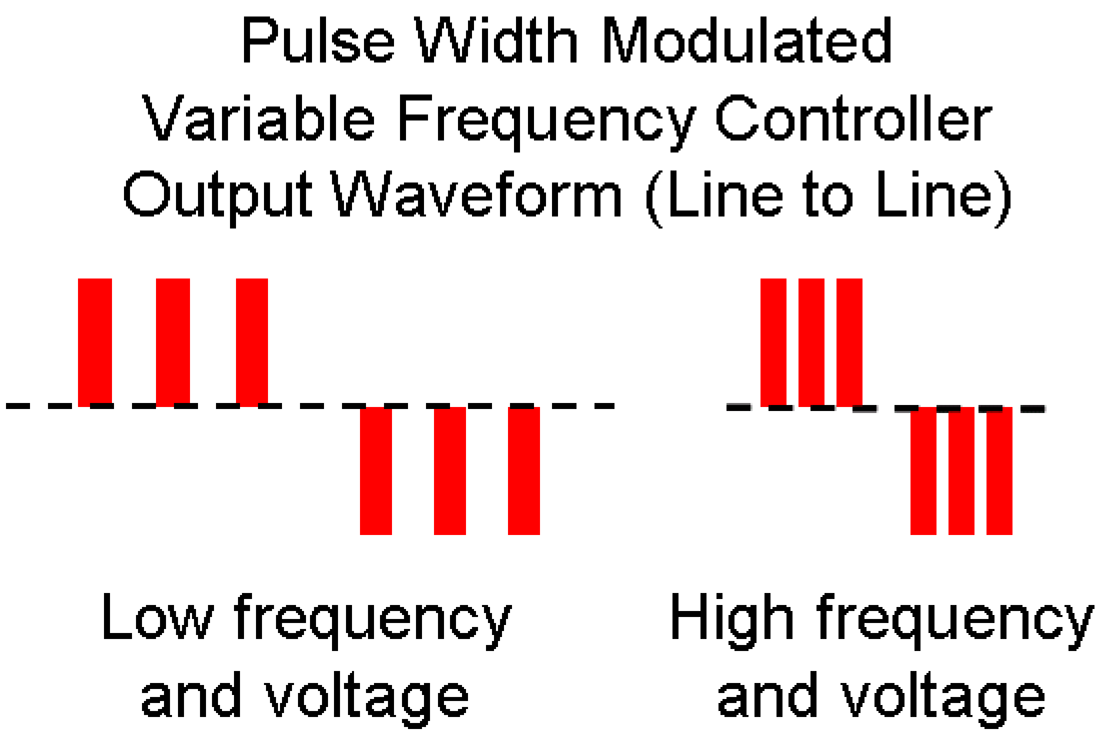
As new types of semiconductor switches have been introduced, these have promptly been applied to inverter circuits at all voltage and current ratings for which suitable devices are available. Introduced in the 1980s, the insulated-gate bipolar transistor (IGBT) became the device used in most VFD inverter circuits in the first decade of the 21st century.

AC motor characteristics require the applied voltage to be proportionally adjusted whenever the frequency is changed in order to deliver the rated torque. For example, if a motor is designed to operate at 460 volts at 60 Hz, the applied voltage must be reduced to 230 volts when the frequency is reduced to 30 Hz. Thus the ratio of volts per hertz must be regulated to a constant value (460/60 = 7.67 V/Hz in this case). For optimum performance, some further voltage adjustment may be necessary especially at low speeds, but constant volts per hertz is the general rule. This ratio can be changed in order to change the torque delivered by the motor.

In addition to this simple volts per hertz control more advanced control methods such as vector control and direct torque control (DTC) exist. These methods adjust the motor voltage in such a way that the magnetic flux and mechanical torque of the motor can be precisely controlled.

The usual method used to achieve variable motor voltage is pulse-width modulation (PWM). With PWM voltage control, the inverter switches are used to construct a quasi-sinusoidal output waveform by a series of narrow voltage pulses with pseudosinusoidal varying pulse durations.

Operation of the motors above rated name plate speed (base speed) is possible, but is limited to conditions that do not require more power than nameplate rating of the motor. This is sometimes called "field weakening" and, for AC motors, means operating at less than rated volts/hertz and above rated name plate speed. Permanent magnet synchronous motors have quite limited field weakening speed range due to the constant magnet flux linkage. Wound rotor synchronous motors and induction motors have much wider speed range. For example, a 100 hp, 460 V, 60 Hz, 1775 RPM (4 pole) induction motor supplied with 460 V, 75 Hz (6.134 V/Hz), would be limited to 60/75 = 80% torque at 125% speed (2218.75 RPM) = 100% power. At higher speeds the induction motor torque has to be limited further due to the lowering of the breakaway torque of the motor. Thus rated power can be typically produced only up to 130...150 % of the rated name plate speed. Wound rotor synchronous motors can be run even higher speeds. In rolling mill drives often 200...300 % of the base speed is used. Naturally the mechanical strength of the rotor and lifetime of the bearings is also limiting the maximum speed of the motor. It is recommended to consult the motor manufacturer if more than 150 % speed is required by the application.



PWM VFD Output Voltage Waveform

An embedded microprocessor governs the overall operation of the VFD controller. The main microprocessor programming is in firmware that is inaccessible to the VFD user. However, some degree of configuration programming and parameter adjustment is usually provided so that the user can customize the VFD controller to suit specific motor and driven equipment requirements.

VFD operator interface

The operator interface provides a means for an operator to start and stop the motor and adjust the operating speed. Additional operator control functions might include reversing and switching between manual speed adjustment and automatic control from an external process control signal. The operator interface often includes an alphanumeric display and/or indication lights and meters to provide information about the operation of the drive. An operator interface keypad and display unit is often provided on the front of the VFD controller as shown in the photograph above. The keypad display can often be cable-connected and mounted a short distance from the VFD controller. Most are also provided with input and output (I/O) terminals for connecting pushbuttons, switches and other operator interface devices or control signals. A serial communications port is also often available to allow the VFD to be configured, adjusted, monitored and controlled using a computer.

VFD operation

When an induction motor is connected to a full voltage supply, it draws several times (up to about 6 times) its rated current. As the load accelerates, the available torque usually drops a little and then rises to a peak while the current remains very high until the motor approaches full speed.

By contrast, when a VFD starts a motor, it initially applies a low frequency and voltage to the motor. The starting frequency is typically 2 Hz or less. Thus starting at such a low frequency avoids the high inrush current that occurs when a motor is started by simply applying the utility (mains) voltage by turning on a switch. After the start of the VFD, the applied frequency and voltage are increased at a controlled rate or ramped up to accelerate the load without drawing excessive current. This starting method typically allows a motor to develop 150% of its rated torque while the VFD is drawing less than 50% of its rated current from the mains in the low speed range. A VFD can be adjusted to produce a steady 150% starting torque from standstill right up to full speed. Note, however, that cooling of the motor is usually not good in the low speed range. Thus running at low speeds even with rated torque for long periods is not possible due to overheating of the motor. If continuous operation with high torque is required in low speeds an external fan is usually needed. The manufacturer of the motor and/or the VFD should specify the cooling requirements for this mode of operation.

In principle, the current on the motor side is in direct proportion of the torque that is generated and the voltage on the motor is in direct proportion of the actual speed, while on the network side, the voltage is constant, thus the current on line side is in direct proportion of the power drawn by the motor, that is U.I or C.N where C is torque and N the speed of the motor (we shall consider losses as well, neglected in this explanation).

(1) n stands for network (grid) and m for motor
(2) C stands for torque [Nm], U for voltage [V], I for current [A], and N for speed [rad/s]
We neglect losses for the moment :
Un.In = Um.Im (same power drawn from network and from motor)
Um.Im = Cm.Nm (motor mechanical power = motor electrical power)
Given Un is a constant (network voltage) we conclude : In = Cm.Nm/Un That is "line current (network) is in direct proportion of motor power".

With a VFD, the stopping sequence is just the opposite as the starting sequence. The frequency and voltage applied to the motor are ramped down at a controlled rate. When the frequency approaches zero, the motor is shut off. A small amount of braking torque is available to help decelerate the load a little faster than it would stop if the motor were simply switched off and allowed to coast. Additional braking torque can be obtained by adding a braking circuit (resistor controlled by a transistor) to dissipate the braking energy. With 4-quadrants rectifiers (active-front-end), the VFD is able to brake the load by applying a reverse torque and reverting the energy back to the network.

Power line harmonics

While PWM allows for nearly sinusoidal currents to be applied to a motor load, the diode rectifier of the VFD takes roughly square-wave current pulses out of the AC grid, creating harmonic distortion in the power line voltage. When the VFD load size is small and the available utility power is large, the effects of VFD systems slicing small chunks out of AC grid generally go unnoticed. Further, in low voltage networks the harmonics caused by single phase equipment such as computers and TVs are such that they are partially cancelled by three-phase diode bridge harmonics.

However, when either a large number of low-current VFDs, or just a few very large-load VFDs are used, they can have a cumulative negative impact on the AC voltages available to other utility customers in the same grid.

When the utility voltage becomes misshapen and distorted the losses in other loads such as normal AC motors are increased. This may in the worst case lead to overheating and shorter operation life. Also substation transformers and compensation capacitors are affected, the latter especially if resonances are aroused by the harmonics.

In order to limit the voltage distortion the owner of the VFDs may be required to install filtering equipment to smooth out the irregular waveform. Alternately, the utility may choose to install filtering equipment of its own at substations affected by the large amount of VFD equipment being used. In high power installations decrease of the harmonics can be obtained by supplying the VSDs from transformers that have different phase shift.

Further, it is possible to use instead of the diode rectifier a similar transistor circuit that is used to control the motor. This kind of rectifier is called active infeed converter in IEC standards. However, manufacturers call it by several names such as active rectifier, ISU (IGBT Supply Unit), AFE (Active Front End) or four quadrant rectifier. With PWM control of the transistors and filter inductors in the supply lines the AC current can be made nearly sinusoidal. Even better attenuation of the harmonics can be obtained by using an LCL (inductor-capacitor-inductor) filter instead of single three-phase filter inductor.

Additional advantage of the active infeed converter over the diode bridge is its ability to feed back the energy from the DC side to the AC grid. Thus no braking resistor is needed and the efficiency of the drive is improved if the drive is frequently required to brake the motor.

Application considerations

The output voltage of a PWM VFD consists of a train of pulses switched at the carrier frequency. Because of the rapid rise time of these pulses, transmission line effects of the cable between the drive and motor must be considered. Since the transmission-line impedance of the cable and motor are different, pulses tend to reflect back from the motor terminals into the cable. The resulting voltages can produce up to twice the rated line voltage for long cable runs, putting high stress on the cable and motor winding and eventual insulation failure. Increasing the cable or motor size/type for long runs and 480v or 600v motors will help offset the stresses imposed upon the equipment due to the VFD (modern 230v single phase motors not effected). At 460 V, the maximum recommended cable distances between VFDs and motors can vary by a factor of 2.5:1. The longer cables distances are allowed at the lower Carrier Switching Frequencies (CSF) of 2.5 kHz. The lower CSF can produce audible noise at the motors. For applications requiring long motor cables VSD manufacturers usually offer du/dt filters that decrease the steepness of the pulses. For very long cables or old motors with insufficient winding insulation more efficient sinus filter is recommended. Expect the older motor's life to shorten. Purchase VFD rated motors for the application.

Further, the rapid rise time of the pulses may cause trouble with the motor bearings. The stray capacitance of the windings provide paths for high frequency currents that close through the bearings. If the voltage between the shaft and the shield of the motor exceeds few volts the stored charge is discharged as a small spark. Repeated sparking causes erosion in the bearing surface that can be seen as fluting pattern. In order to prevent sparking the motor cable should provide a low impedance return path from the motor frame back to the inverter. Thus it is essential to use a cable designed to be used with VSDs.

In big motors a slip ring with brush can be used to provide a bypass path for the bearing currents. Alternatively isolated bearings can be used.

The 2.5 kHz and 5 kHz CSFs cause fewer motor bearing problems than the 20 kHz CSFs. Shorter cables are recommended at the higher CSF of 20 kHz. The minimum CSF for synchronize tracking of multiple conveyors is 8 kHz.

The high frequency current ripple in the motor cables may also cause interference with other cabling in the building. This is another reason to use a motor cable designed for VSDs that has a symmetrical three-phase structure and good shielding. Further, it is highly recommended to route the motor cables as far away from signal cables as possible.

Available VFD power ratings

Variable frequency drives are available with voltage and current ratings to match the majority of 3-phase motors that are manufactured for operation from utility (mains) power. VFD controllers designed to operate at 111 V to 690 V are often classified as low voltage units. Low voltage units are typically designed for use with motors rated to deliver 0.2 kW or 1/4 horsepower (hp) up to several megawatts. For example, the largest ABB ACS800 single drives are rated for 5.6 MW . Medium voltage VFD controllers are designed to operate at 2,400/4,162 V (60 Hz), 3,000 V (50 Hz) or up to 10 kV. In some applications a step up transformer is placed between a low voltage drive and a medium voltage load. Medium voltage units are typically designed for use with motors rated to deliver 375 kW or 500 hp and above. Medium voltage drives rated above 7 kV and 5,000 or 10,000 hp should probably be considered to be one-of-a-kind (one-off) designs.

Medium voltage drives are generally rated amongst the following voltages : 2,3 KV - 3,3 Kv - 4 Kv - 6 Kv - 11 Kv
The in-between voltages are generally possible as well. The power of MV drives is generally in the range of 0,3 to 100 MW however involving a range a several different type of drives with different technologies.

Dynamic braking

Using the motor as a generator to absorb energy from the system is called dynamic braking. Dynamic braking stops the system more quickly than coasting. Since dynamic braking requires relative motion of the motor's parts, it becomes less effective at low speed and cannot be used to hold a load at a stopped position. During normal braking of an electric motor the electrical energy produced by the motor is dissipated as heat inside of the rotor, which increases the likelihood of damage and eventual failure. Therefore, some systems transfer this energy to an outside bank of resistors. Cooling fans may be used to protect the resistors from damage. Modern systems have thermal monitoring, so if the temperature of the bank becomes excessive, it will be switched off.

Regenerative variable-frequency drives

Regenerative AC drives have the capacity to recover the braking energy of an overhauling load and return it to the power system.

Line regenerative variable frequency drives, showing capacitors(top cylinders)and inductors attached which filter the regenerated power.

Cycloconverters and current-source inverters inherently allow return of energy from the load to the line; voltage-source inverters require an additional converter to return energy to the supply.

Regeneration is only useful in variable-frequency drives where the value of the recovered energy is large compared to the extra cost of a regenerative system, and if the system requires frequent braking and starting. An example would be use in conveyor belt during manufacturing where it should stop for every few minutes, so that the parts can be assembled correctly and moves on. Another example is a crane, where the hoist motor stops and reverses frequently, and braking is required to slow the load during lowering.

Regenerative variable-frequency drives are widely used where speed control of overhauling loads is required.

Brushless DC motor drives

Much of the same logic contained in large, powerful VFDs is also embedded in small brushless DC motors such as those commonly used in computer fans. In this case, the chopper usually converts a low DC voltage (such as 12 volts) to the three-phase current used to drive the electromagnets that turn the permanent magnet rotor.

Chapter 4

Line Shaft

Four wool spinning machines driven by belts from an overhead lineshaft (Leipzig, Germany, circa 1925)

A **line shaft** is a power transmission system used extensively during the Industrial Revolution. Prior to the widespread use of electric motors small enough to be connected directly to each piece of machinery, line shafting was used to distribute power from a large central power source to machinery throughout an industrial complex. The central power source could be a water wheel or turbine, animal power, a stationary steam engine, a steam traction engine, a portable engine, or, in later years, a single large electric motor. Power was distributed from the shaft to the machinery by a system of belts,and pulleys.

History

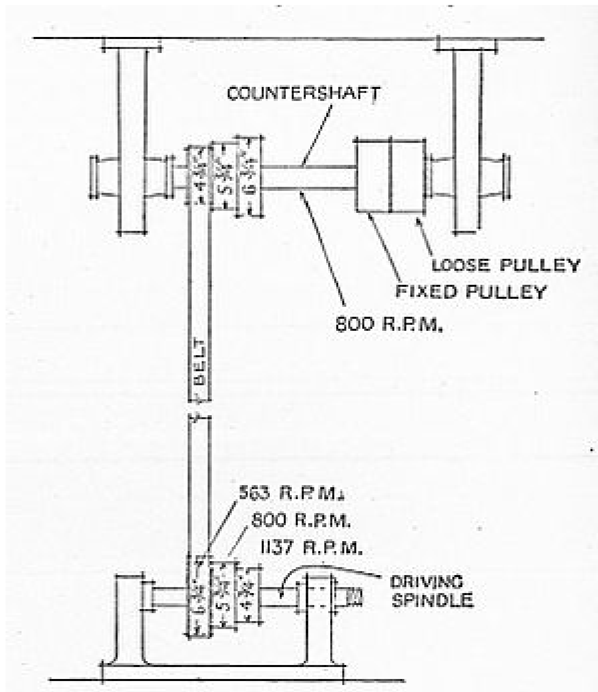
Early version of line shafts date back into the 18th century, but truly came of age in the early 19th century industrialization and manufacturing. Line shafts were widely used in manufacturing, woodworking shops, machine shops, saw mills and grist mills.

Flat belt drive systems became popular in the UK from the 1870s, with the firms of J E Wood and W & J Galloway & Sons prominent in their introduction. Both of these firms manufactured stationary steam engines and the continuing demand for more power and reliability could be met not merely by improved engine technology but also improved methods of transferring power from the engines to the looms and similar machinery which they were intended to service. The use of flat belts was already common in the US but rare in Britain until this time. The advantages included less noise and less wasted energy in the friction losses inherent in the previously common drive shafts and their associated gearing. Also, maintenance was simpler and cheaper, and it was a more convenient method for the arrangement of power drives such that if one part were to fail then it would not cause loss of power to all sections of a factory or mill. These systems were in turn superseded in popularity by rope drive methods.

Line shafting fell out of favor in the early-to-mid 20th century with the widespread availability of electrical power and availability of compact electric motors. Such independent motors are far less maintenance intensive than maintaining a line shaft system. Those systems in place tended to be converted to power from a large internal combustion engine or large electric motor. Some systems were broken up with separate motors driving different parts of what was one system. Most systems were out of service by the mid-20th century and relatively few remain in the 21st century, even fewer in their original location and configuration.

Most paper machines used steam turbine -powered line shafts until the 1980s, since then many have been replaced with sectional electric drives.

Operation



Variable speed belt drive for a lathe. The fixed pulley on the upper shaft is driven at constant speed by a belt from the power source. The loose pulley ('idler') allows the machine to be stopped in isolation – necessary for changing speed. The stepped pulleys (left) provide three drive speeds for the machine tool (not shown), depending on which pair of pulleys is connected by the belt.

A typical line shaft would be suspended from the ceiling of one area and would run the length of that area. One pulley on the shaft would receive the power from the a parent line shaft elsewhere in the building. The other pulleys would supply power to pulleys on each individual machine or to subsequent line shafts. In manufacturing where there were a large number of machines performing the same tasks, the design of the system was fairly regular and repeated. In other applications such as machine and wood shops where there was a variety of machines with different orientations and power requirements, the system would appear erratic and inconsistent with many different shafting directions and pulley sizes. Shafts were usually horizontal and overhead but occasionally were vertical and could be underground. Shafts were usually rigid steel, made up of several parts bolted together at flanges. The shafts were suspended by hangers with bearings at certain intervals of length. The distance depended on the weight of the shaft and the number of pulleys. The shafts had to be kept aligned or the stress would overheat the bearings and could break the shaft. The bearings were usually friction type and had to be kept lubricated.

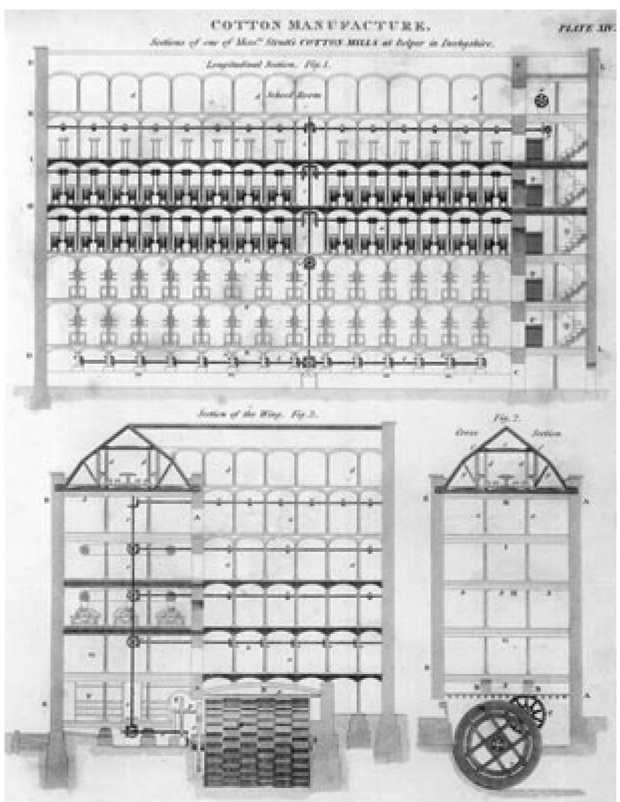
In the earliest applications power was transmitted between pulleys using loops of rope on grooved pulleys. This method is extremely rare today, dating mostly from the 18th century. Flat belts on flat pulleys or drums were the most common method during the

19th and early 20th century. The belts were generally tanned leather or cotton duck impregnated with rubber. Leather belts were fastened in loops with rawhide or wire lacing, lap joints and glue, or one of several types of steel fasteners. Cotton duck belts usually used metal fasteners or were melted together with heat. The leather belts were run with the hair side against the pulleys for best traction. The belts needed periodic cleaning and conditioning to keep them in good condition. Belts were often twisted 180 degrees per leg and reversed on the receiving pulley to cause the second shaft to rotate in the opposite direction.

Pulleys were constructed of wood, iron, steel or a combination thereof. Varying sizes of pulleys were used in conjunction to change the speed of rotation. For example a 40" pulley at 100 RPM would turn a 20" pulley at 200 RPM. Pulleys solidly attached to the shaft could be combined with adjacent pulleys that turned freely on the shaft (idlers). In this configuration the belt could be maneuvered onto the idler to stop power transmission or onto the solid pulley to convey the power. This arrangement was often used near machines to provide a means of shutting the machine off when not in use. Usually at the last belt feeding power to a machine, a pair of stepped pulleys could be used to give a variety of speed settings for the machine.

Occasionally gears were used between shafts to change speed rather than belts and different sized pulleys, but this seems to have been relatively uncommon.

Early Examples



Jedediah Strutt, North Mill at Belper in 1819, showing vertical shaft leading from the 18 feet (5.5 m) waterwheel, to horizontal drive shafts running the length of each floor on each floor

In an early example, Jedediah Strutt's water-powered cotton mill, North Mill in Belper, built in 1776, all the power to operate the machinery came from a 18 feet (5.5 m) water wheel.

Preservation

Original Systems

- East Broad Top Railroad and Coal Company. Rockhill Furnace, PA (inoperable wood shop, blacksmiths shop, foundry)
- Longleaf Lumber Company/Southern Forest Heritage Museum, Longleaf, LA (partially operable - machine tools, sawmill)
- Sierra Railroad Shops/Railtown 1897 State Historic Park, Jamestown, CA (operable - machine tools, blachsmith shop)
- Empire Mine State Park machine Shop, Grass Valley, CA (??? - machine tools)
- Hagley Museum, Wilmington, DE
- Stott Park Bobbin Mill, Cumbria, England (???)
- Mingus Mill, Great Smokey Mountains National Park, SC (partially operable - grain mill)
- Hanford Mills Museum, East Meredith, NY (???)
- Slater Mill Historic Site, Pawtucket, RI (???)
- Thomas Edison National Historical Park, West Orange, NJ (??? - Machine Tools)
- W J Doran Company, Waupaca, WI, (fully operational - machine tools)
- Shelsley Watermill, Shelsley Walsh, Worcester, UK (partially operable - grain mill)
- Cruiser Olympia, Philadelphia PA (operational machine shop)

Reconstructed or Demonstration Systems

- Smithsonian Institution, Arts and Industries Building, Washington DC (machine tools)
- White River Valley Antique Association, Enora, IN (machine and woodworking tools)
- Denton Farmpark, Denton, NC (machine tools)
- Cincinnati History Museum, Cincinnati, OH (machine tools)
- Henry Ford Museum and Greenfield Village, Dearborn, MI (machine tools)
- Molly Kathleen Mine, Clear Creek, CO (sawmill)
- Boott Mills, Lowell, MA (power cotton looms)
- Silver Dollar City, Branson, MO (woodworking tools and bakery machinery)
- Tuckahoe Steam & Gas Association, Easton, MD (machine tools)

Chapter 5

Adjustable-Speed Drive

Adjustable speed drive (ASD) or variable-speed drive (VSD) describes equipment used to control the speed of machinery. Many industrial processes such as assembly lines must operate at different speeds for different products. Where process conditions demand adjustment of flow from a pump or fan, varying the speed of the drive may save energy compared with other techniques for flow control.

Where speeds may be selected from several different pre-set ranges, usually the drive is said to be "adjustable" speed. If the output speed can be changed without steps over a range, the drive is usually referred to as "variable speed".

Adjustable and variable speed drives may be purely mechanical (termed 'Variators'), electromechanical, hydraulic, or electronic.

Line regenerative variable frequency drives, showing capacitors(top cylinders)and inductors attached which filter the regenerated power.

Fixed speeds of electric motors

Alternating-current electric motors run at speeds closely determined by the number of poles in the motor and the frequency of the alternating current supply. This is unlike the steam engine, which can be made to run over a range of speeds by adjusting the timing and duration of valves admitting steam to the cylinder.

AC motors can be made with several sets of poles, which can be chosen to give one of several different speeds (say, 720/1800 RPM for a 60 Hz motor). The number of different speeds available is limited by the expense of providing multiple sets of windings. If many different speeds or continuously variable speeds are required, other methods are required.

Direct-current motors allow for changes of speed by adjusting the shunt field current. Another way of changing speed of a direct current motor is to change the voltage applied to the armature.

An adjustable speed drive might consist of an electric motor and controller that is used to adjust the motor's operating speed. The combination of a constant-speed motor and a steplessly adjustable mechanical speed-changing device might also be called an adjustable speed drive. Electronic variable frequency drives are rapidly making older technology redundant.

Reasons for using adjustable speed drives

Process control and energy conservation are the two primary reasons for using an adjustable speed drive. Historically, adjustable speed drives were developed for process control, but energy conservation has emerged as an equally important objective.

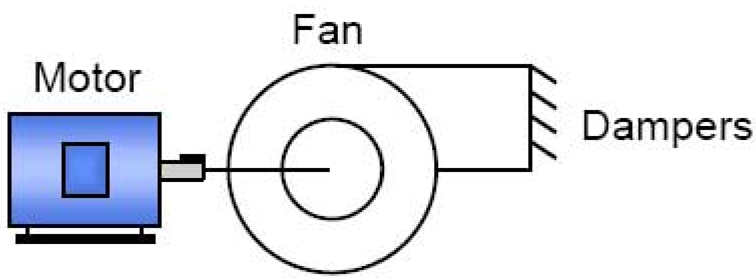
Adjusting speed as a means of controlling a process

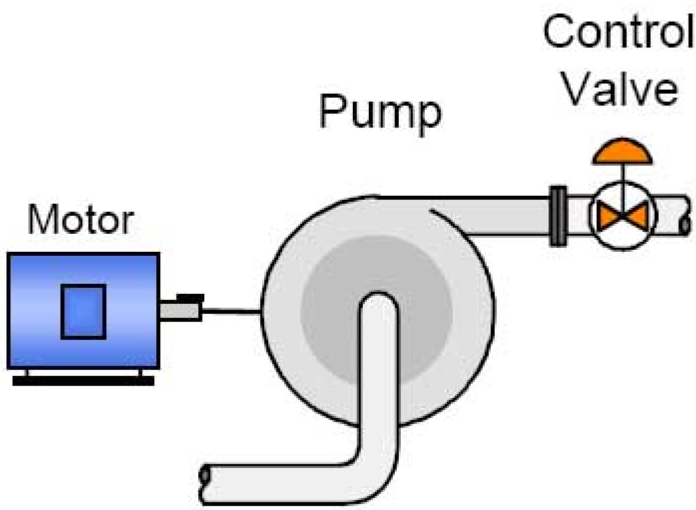
The following are process control benefits that might be provided by an adjustable speed drive:

- Smoother operation
- Acceleration control
- Different operating speed for each process recipe
- Compensate for changing process variables
- Allow slow operation for setup purposes
- Adjust the rate of production
- Allow accurate positioning
- Control torque or tension

Example

An adjustable speed drive can often provide smoother operation compared to an alternative fixed speed mode of operation. For example, in a sewage lift station sewage usually flows through sewer pipes under the force of gravity to a wet well location. From there it is pumped up to a treatment process. When fixed speed pumps are used, the pumps are set to start when the level of the liquid in the wet well reaches some high point and stop when the level has been reduced to a low point. Cycling the pumps on and off results in frequent high surges of electric current to start the motors resulting in electromagnetic and thermal stresses in the motors and power control equipment, the pumps and pipes are subjected to mechanical and hydraulic stresses, and the sewage treatment process is forced to accommodate surges in the flow of sewage through the process. When adjustable speed drives are used, the pumps operate continuously at a speed that increases as the wet well level increases. This matches the outflow to the average inflow and provides a much smoother operation of the process.





Saving energy by using adjustable speed drives

An adjustable speed drive often uses less energy than an alternative fixed speed mode of operation. Fans and pumps are the most common energy saving applications. When a fan is driven by a fixed speed motor, the airflow may sometimes be higher than it needs to be. Airflow can be regulated by using a damper to restrict the flow, but it is more efficient to regulate the airflow by regulating the speed of the motor. It follows from the affinity laws that reducing fan speed to 50% results in a power consumption drop to 12.5%.

Types of adjustable speed drives

Speed adjustment techniques have been used in transmitting mechanical power to machinery since the earliest use of powered machinery. Before electric motors were invented, mechanical speed changers were used to control the mechanical power provided by water wheels and steam engines. When electric motors came into use, means of controlling their speed were developed almost immediately. Today, various types of mechanical drives, hydraulic drives and electric drives compete with one another in the industrial drives market.

Mechanical adjustable speed drives

There are two types of mechanical drives, variable pitch drives and traction drives.

Variable pitch drives are pulley and belt drives in which the pitch diameter of one or both pulleys can be adjusted.

Traction drives transmit power through metal rollers running against mating metal rollers. The input/output speed ratio is adjusted by moving the rollers to change the diameters of the contact path. Many different roller shapes and mechanical designs have been used.

Hydraulic adjustable speed drives

There are three types of hydraulic drives, those are : hydrostatic drives, hydrodynamic drives and hydroviscous drives.

A **hydrostatic drive** consists of a hydraulic pump and a hydraulic motor. Since positive displacement pumps and motors are used, one revolution of the pump or motor corresponds to a set volume of fluid flow that is determined by the displacement regardless of speed or torque. Speed is regulated by regulating the fluid flow with a valve or by changing the displacement of the pump or motor. Many different design variations have been used. A swash plate drive employs an axial piston pump and/or motor in which the swash plate angle can be changed to adjust the displacement and thus adjust the speed.

Hydrodynamic drives or fluid couplings use oil to transmit torque between an impeller on the constant-speed input shaft and a rotor on the adjustable-speed output shaft. The torque converter in the automatic transmission of a car is a hydrodynamic drive.

A **hydroviscous drive** consists of one or more discs or connected to the input shaft pressed against a similar disc or discs connected to the output shaft. Torque is transmitted from the input shaft to the output shaft through an oil film between the discs. The transmitted torque is proportional to the pressure exerted by a hydraulic cylinder that presses the discs together.

Continuously variable transmission (CVT)

Mechanical and hydraulic adjustable speed drives are usually called transmissions or continuously variable transmissions when they are used in vehicles, farm equipment and some other types of equipment.

Electric adjustable speed drives

There are three general categories of electric drives: DC motor drives, eddy current drives and AC motor drives. Each of these general types can be further divided into numerous variations. Electric drives generally include both an electric motor and a speed control unit or system. The term *drive* is often applied to the controller without the motor. In the early days of electric drive technology, electromechanical control systems were used. Later, electronic controllers were designed using various types of vacuum tubes. As suitable solid state electronic components became available, new controller designs incorporated the latest electronic technology.

DC drives

DC drives are DC motor speed control systems. Since the speed of a DC motor is directly proportional to armature voltage and inversely proportional to motor flux (which is a function of field current), either armature voltage or field current can be used to control speed. Several types of DC motors are described in the electric motor article. The electric motor article also describes electronic speed controls used with various types of DC motors.

Eddy current drives

An eddy current drive consists of a fixed speed motor and an eddy current clutch. The clutch contains a fixed speed rotor and an adjustable speed rotor separated by a small air gap. A direct current in a field coil produces a magnetic field that determines the torque transmitted from the input rotor to the output rotor. The controller provides closed loop speed regulation by varying clutch current, only allowing the clutch to transmit enough torque to operate at the desired speed. Speed feedback is typically provided via an integral AC tachometer.

Eddy current drives are a type of *slip controlled drive*. Slip controlled drives are generally less efficient than other types of drives. The motor develops the torque required by the load and operates at full speed. The output shaft transmits the same torque to the load, but turns at a slower speed. Since power is proportional to torque multiplied by speed, the input power is proportional to motor speed times operating torque while the output power is output speed times operating torque. The difference between the motor speed and the output speed is called the *slip speed*. Power proportional to the slip speed times operating torque is dissipated as heat in the clutch.

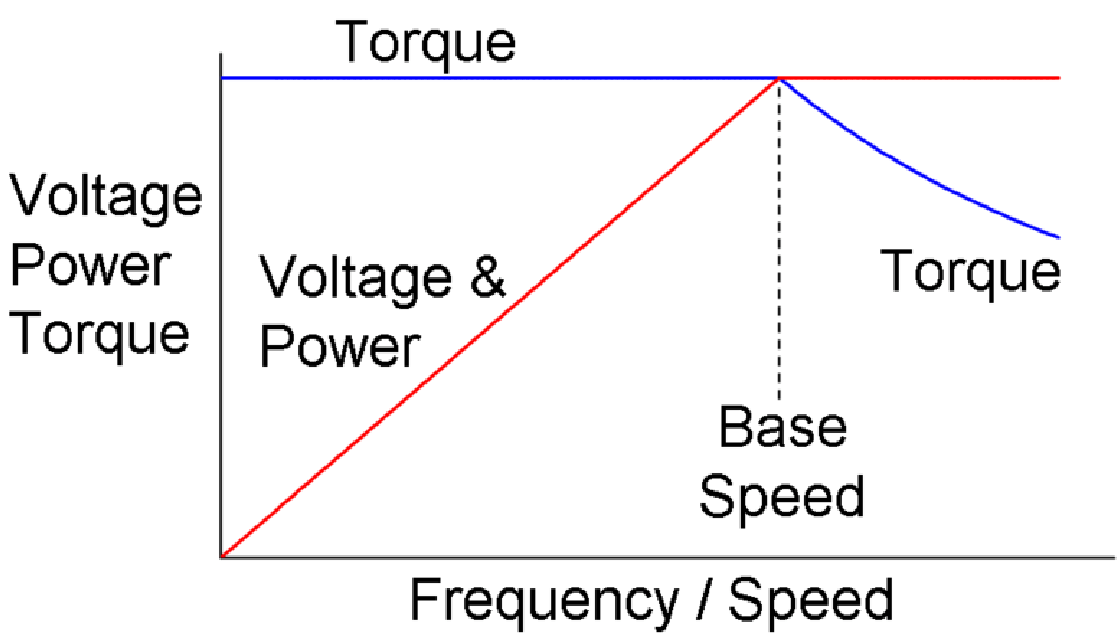
AC drives

AC drives are AC motor speed control systems.

Slip controlled drives control the speed of an induction motor by increasing a motor's slip, either by reducing the voltage applied to the motor, or increasing the resistance of the rotor windings. Because they are generally less efficient than other types of drives, slip controlled drives have lost popularity and have recently been used only in special situations.

In larger ratings (more than a few kilowatts), a wound-rotor motor has its rotor connected to a converter that returns energy to the power system, converting it from low slip frequency to the line freqeuncy. This reclaims the energy that would otherwise be wasted in rotor circuit resistors. These are called "slip energy recovery drives" and are used on such applications as forced-draft blowers for boilers. An electromechanical version using a rectifier, DC motor and AC generator is called a *Kramer drive*.

Adjustable-frequency drives (AFD) control the speed of either an induction motor or a synchronous motor by adjusting the frequency of the power supplied to the motor. Adjustable frequency drives are also known as variable-frequency drives (VFD).



When changing the frequency of the power supplied to an AC motor, the ratio of the applied voltage to the applied frequency (V/Hz) is generally maintained at a constant value between the minimum and maximum operating frequencies. Operation at a constant voltage (reduced V/Hz) above a given frequency provides reduced torque capability and constant power capability above that frequency. The frequency or speed at which constant-voltage operation begins is called the *base* frequency or speed. Whether the applied voltage is regulated directly or indirectly, the V/Hz tends to follow the general pattern described for the performance described. The variable-frequency drive article provides additional information on electronic speed controls used with various types of AC motors.

Regenerative variable-Frequency drives

Regenerative AC drives are a type of AC drive and have the capacity to recover the braking energy of an overhauling load and return it to the power system.

Chapter 6

Fluid Coupling

A **fluid coupling** is a hydrodynamic device used to transmit rotating mechanical power. It has been used in automobile transmissions as an alternative to a mechanical clutch. It also has widespread application in marine and industrial machine drives, where variable speed operation and/or controlled start-up without shock loading of the power transmission system is essential.

History

The **fluid coupling** originates from the work of Dr. Hermann Föttinger, who was the chief designer at the AG Vulcan Works in Stettin. His patents from 1905 covered both fluid couplings and torque converters.

In 1930 Harold Sinclair, working with the Daimler company, devised a transmission system using a fluid coupling and planetary gearing for buses in an attempt to mitigate the lurching he had experienced while riding on London buses during the 1920s.

In 1939 General Motors Corporation introduced Hydramatic drive, the first fully automatic automotive transmission system installed in a mass produced automobile. The Hydramatic employed a fluid coupling.

The first Diesel locomotives using fluid couplings were also produced in the 1930s

Overview

A fluid coupling consists of three components, plus the hydraulic fluid:

- The housing, also known as the *shell* (which must have an oil tight seal around the drive shafts), contains the fluid and turbines.
- Two turbines (fan like components):

  - One connected to the input shaft; known as the *pump* or *impellor*, *primary wheel input turbine*
  - The other connected to the output shaft, known as the *turbine*, *output turbine*, *secondary wheel* or *runner*

The driving turbine, known as the 'pump', (or *driving torus*) is rotated by the prime mover, which is typically an internal combustion engine or electric motor. The impellor's motion imparts both outwards linear and rotational motion to the fluid.

The hydraulic fluid is directed by the 'pump' whose shape forces the flow in the direction of the 'output turbine' (or *driven torus*). Here, any difference in the angular velocities of 'input stage' and 'output stage' result in a net force on the 'output turbine' causing a torque; thus causing it to rotate in the same direction as the pump.

The motion of the fluid is effectively toroidal - travelling in one direction on paths that can be visualised as being on the surface of a torus:

- If there is a difference between input and output angular velocities the motion has a component which is circular (i.e. round the rings formed by sections of the torus)
- If the input and output stages have identical angular velocities there is no net centripetal force - and the motion of the fluid is circular and co-axial with the axis of rotation (i.e. round the edges of a torus), there is no flow of fluid from one turbine to the other.

Stall speed

An important characteristic of a fluid coupling is its stall speed. The stall speed is defined as the highest speed at which the pump can turn when the output turbine is locked and maximum input power is applied. Under stall conditions all of the engine's power would be dissipated in the fluid coupling as heat, possibly leading to damage.

Step-circuit coupling

A modification to the simple fluid coupling is the step-circuit coupling which was formerly manufactured as the "STC coupling" by the Fluidrive Engineering Company.

The STC coupling contains a reservoir to which some, but not all, of the oil gravitates when the output shaft is stalled. This reduces the "drag" on the input shaft, resulting in reduced fuel consumption when idling and a reduction in the vehicle's tendency to "creep".

When the output shaft begins to rotate, the oil is thrown out of the reservoir by centrifugal force, and returns to the main body of the coupling, so that normal power transmission is restored.

Slip

A fluid coupling cannot develop output torque when the input and output angular velocities are identical. Hence a fluid coupling cannot achieve 100 percent power transmission efficiency. Due to slippage that will occur in any fluid coupling under load, some power will always be lost in fluid friction and turbulence, and dissipated as heat.

The very best efficiency a fluid coupling can achieve is 94%, that is for every 100 revolutions input, there will be 94 revolutions output. Like other fluid dynamical devices, its efficiency tends to increase gradually with increasing scale, as measured by the Reynolds number.

Hydraulic fluid

As a fluid coupling operates kinetically, low viscosity fluids are preferred. Generally speaking, multi-grade motor oils or automatic transmission fluids are used. Increasing density of the fluid increases the amount of torque that can be transmitted at a given input speed.

Hydrodynamic braking

Fluid couplings can also act as hydrodynamic brakes, dissipating rotational energy as heat through frictional forces (both viscous and fluid/container). When a fluid coupling is used for braking it is also known as a *retarder*.

Applications

Industrial

Fluid couplings are used in many industrial application involving rotational power, especially in machine drives that involve high-inertia starts or constant cyclic loading.

Rail transportation

Fluid couplings are found in some Diesel locomotives as part of the power transmission system. Self-Changing Gears made semi-automatic transmissions for British Rail, and Voith manufacture turbo-transmissions for railcars and diesel multiple units which contain various combinations of fluid couplings and torque converters.

Automotive

Fluid couplings were used in a variety of early semi-automatic transmissions and automatic transmissions. Since the late 1940s, the hydrodynamic torque converter has replaced the fluid coupling in automotive applications.

In automotive applications, the pump typically is connected to the flywheel of the engine—in fact, the coupling's enclosure may be part of the flywheel proper, and thus is turned by the engine's crankshaft. The turbine is connected to the input shaft of the transmission. While the transmission is in gear, as engine speed increases torque is transferred from the engine to the input shaft by the motion of the fluid, propelling the vehicle. In this regard, the behavior of the fluid coupling strongly resembles that of a mechanical clutch driving a manual transmission.

Fluid flywheels, as distinct from torque converters, are best known for their use in Daimler cars in conjunction with a Wilson pre-selector gearbox. Daimler used these throughout their range of luxury cars, until switching to automatic gearboxes with the 1958 Majestic. Daimler and Alvis were both also known for their military vehicles and armored cars, some of which also used the combination of pre-selector gearbox and fluid flywheel.

Aviation

The most prominent use of fluid couplings in aeronautical applications was in the Wright turbo-compound reciprocating engine, in which three power recovery turbines extracted approximately 20 percent of the energy or about 500 horsepower (370 kW) from the engine's exhaust gases and then, using three fluid couplings and gearing, converted low-torque high-speed turbine rotation to low-speed, high-torque output to drive the propeller.

Calculations

Generally speaking, the power transmitting capability of a given fluid coupling is strongly related to pump speed, a characteristic that generally works well with applications where the applied load doesn't fluctuate to a great degree. The torque transmitting capacity of any hydrodynamic coupling can be described by the expression $r(N^2)(D^5)$, where r is the mass density of the fluid, N is the impeller speed, and D is the impeller diameter. In the case of automotive applications, where loading can vary to considerable extremes, $r(N^2)(D^5)$ is only an approximation. Stop-and-go driving will tend to operate the coupling in its least efficient range, causing an adverse effect on fuel economy.

Manufacture

Fluid couplings are relatively simple components to produce. For example, the turbines can be aluminum castings or steel stampings, and the housing can also be a casting or made from stamped or forged steel.

Manufacturers of industrial fluid couplings include Voith, Transfluid, TwinDisc, Siemens, PARAG, Fluidomat, and Reuland Electric.

Chapter 7

Wire Rope

Steel wire rope (right hand lay)

Wire rope is a type of rope which consists of several strands of metal wire laid (or 'twisted') into a helix. Initially wrought iron wires were used, but today steel is the main material used for wire ropes.

Historically wire rope evolved from steel chains which had a record of mechanical failure. While flaws in chain links or solid steel bars can lead to catastrophic failure, flaws in the wires making up a steel cable are less critical as the other wires easily take up the load. Friction between the individual wires and strands, as a consequence of their twist, further compensates for any flaws. This method of minimising the effect of flaws may also be seen in Damascus steel, employing multiple folding or laminations.

History and materials

Modern wire rope was invented by the German mining engineer Wilhelm Ducay in the years between 1831 and 1834 for use in mining in the Harz Mountains in Clausthal, Lower Saxony, Germany. It was quickly accepted because it proved superior to ropes made of hemp or to metal chains, such as had been used before.

Wilhelm Albert's first ropes consisted of wires twisted about a hemp rope core, six such strands then being twisted around another hemp rope core in alternating directions for extra stability. Earlier forms of wire rope had been made by covering a bundle of wires with hemp.

In America wire rope was later manufactured by John A. Roebling, forming the basis for his success in suspension bridge building. Roebling introduced a number of innovations in the design, materials and manufacture of wire rope.

Manufacturing a wire rope is similar to making one from natural fibres. The individual wires are first twisted into a strand, then six or so such strands again twisted around a core. This core may consist of steel, but also of natural fibres such as sisal, manila, henequen, jute, or hemp. This is used to cushion off stress forces when bending the rope.

This flexibility is particularly vital in ropes used in machinery such as cranes or elevators as well as ropes used in transportation modes such as cable cars, cable railways, funiculars and aerial lifts. It is not quite so essential in suspension bridges and similar uses.

Wire rope is often sold with vinyl and nylon coatings. This increases weather resistance and overall durability, however it can lead to weak joints if the coating is not removed correctly underneath joints and connections.

Lay of wire rope

Left-hand ordinary lay (LHOL) wire rope (close-up). Right-hand lay strands are laid into a left-hand lay rope.

Right-hand Lang's lay (RHLL) wire rope (close-up). Right-hand lay strands are laid into a right-hand lay rope.

The lay of a wire rope describes the manner in which either the wires in a strand, or the strands in the rope, are laid in a helix.

Left and right hand lay

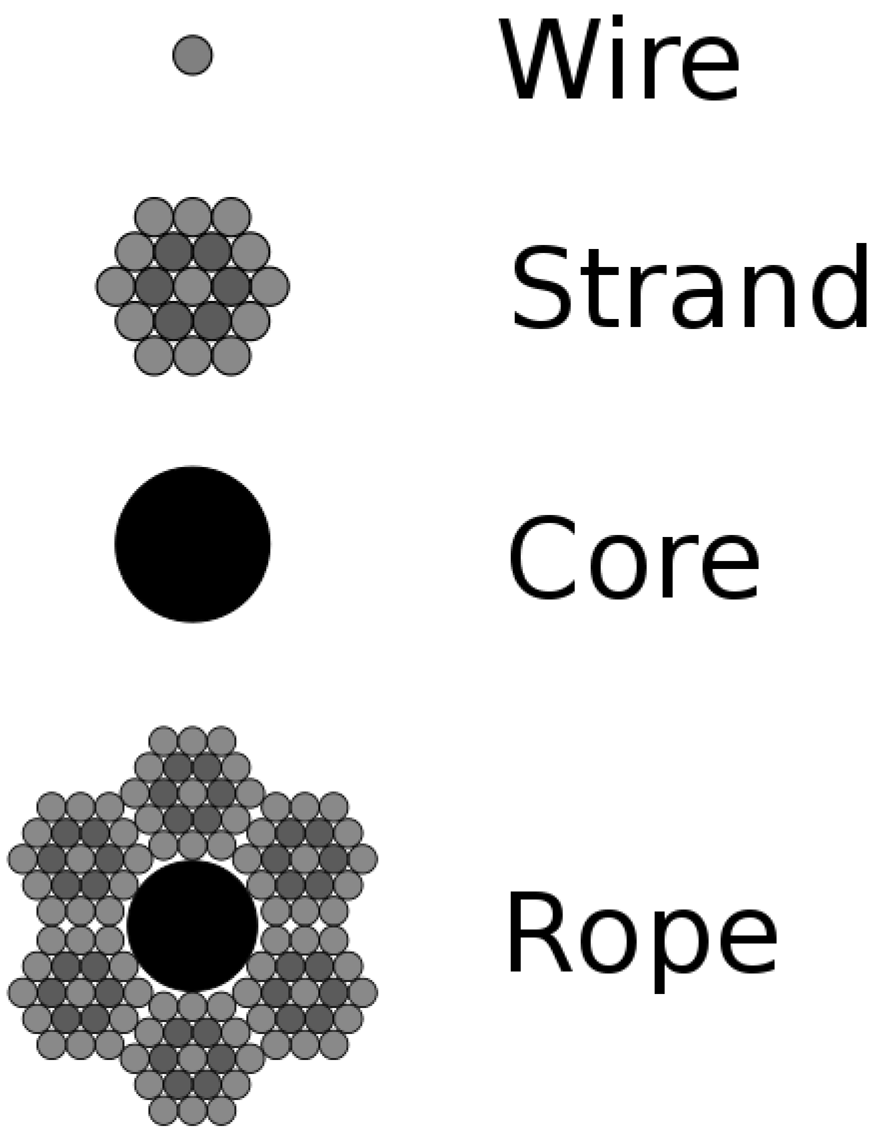
Left hand lay or right hand lay describe the manner in which the strands are laid to form the rope. To determine the lay of strands in the rope, a viewer looks at the rope as it points away from them. If the strands appear to turn in a clockwise direction, or like a right-hand thread, as the strands progress away from the viewer, the rope has a right hand lay. The picture of steel wire rope on this page shows a rope with right hand lay. If the strands appear to turn in an anti-clockwise direction, or like a left-hand thread, as the strands progress away from the viewer, the rope has a left hand lay. (The rope in the left hand lay photo shows one left hand lay rope from left to right and top to bottom, with 5 right hand lay strands, and part of a sixth in the upper left. It is not 5 right hand lay ropes adjacent to each other.)

Ordinary, Lang's and alternate lay

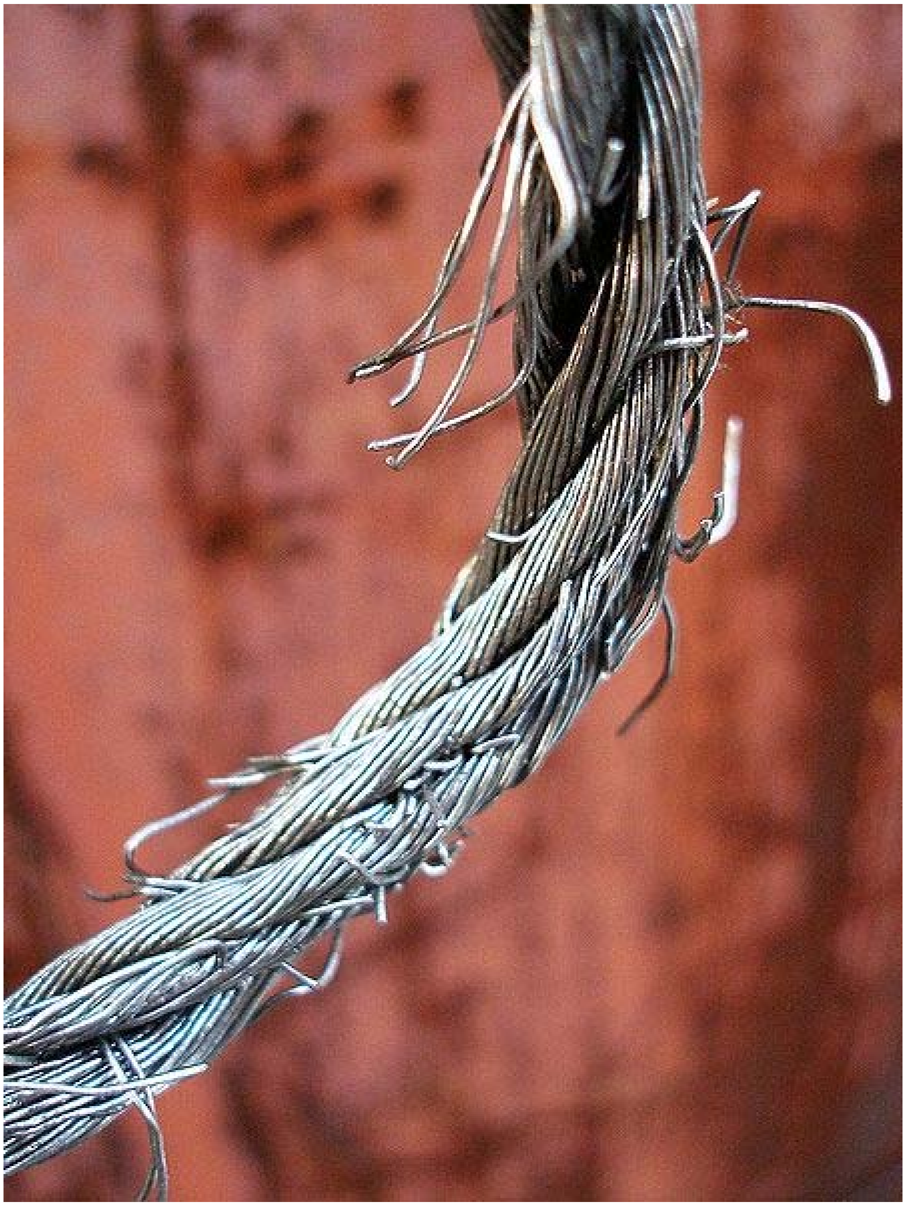
Ordinary and Ducay's lay describe the manner in which the wires are laid to form a strand of the wire rope. To determine which has been used, first identify if left or right hand lay has been used to make the rope. Then identify if a right or left hand lay has been used to twist the wires in each strand. (On ordinary lay, the outer wires approximately follow the alignment of the rope: with Lang's lay they are cross at an angle of about 45°.) Lang's laid rope is able to flex over sheaves more easily (with less damage) but it has the disadvantage of having a high torque tendency (it tends to untwist when tension load is applied) compared with ordinary laid rope. Untwisting can be dangerous with a steel-cored rope: load is shed from the strands and may cause the core to fail as it becomes higher loaded. For this reason, swivel termination units can be dangerous.

Ordinary lay	The lay of wires in each strand is in the opposite direction to the lay of the strands that form the wire.
Lang's lay	The lay of wires in each strand is in the same direction as the lay of the strands that form the wire.
Alternate lay	Strands alternate between Lang's lay and ordinary lay; e.g.: in a 6-strand wire, 3 strands are ordinary lay, and 3 are Lang's lay.
Regular lay	Alternate term for ordinary lay.
Albert's lay	Archaic term for Lang's lay.
Reverse lay	Alternate term for alternate lay.
Spring lay	It refers to a specific construction type of wire rope.

Construction and specification



Wire rope construction



This image of a fraying wire rope shows some individual wires.

The specification of a wire rope type – including the number of wires per strand, the number of strands, and the lay of the rope – is documented using a commonly accepted coding system, consisting of a number of abbreviations.

This is easily demonstrated with a simple example. The rope shown in the figure "Wire rope construction" is designated thus: **6x19 FC RH OL FSWR**

6	Number of strands that make up the rope
19	Number of wires that make up each strand
FC	Fibre core

RH Right hand lay

OL Ordinary lay

GSWR Galvanized Steel Wire Rope

FSWR Flexible steel wire rope

Each of the sections of the wire rope designation described above is variable. There are therefore a large number of combinations of wire rope that can be specified in this manner. The following abbreviations are commonly used to specify a wire rope.

Abbr.	Description
FC	Fibre core
FSWR	Flexible steel wire rope
FW	Filler wire
IWR	Independent wire rope
IWRC	Independent wire rope core
J	Jute (fibre)
LH	Left hand lay
LL	Lang's lay
NR	Non-rotating
OL	Ordinary lay
RH	Right hand lay
S	Seale
SF	Seale filler wire
SW	Seale Warrington
SWL	Safe working load
TS	Triangular strand
W	Warrington
WF	Warriflex
WLL	Working load limit
WS	Warrington Seale

Warrington differs from the other types (Filler Wire and Seale construction) in that the outside layer of wires in each strand of the wire rope is composed of wires alternately large and small. The outside wires of both the Filler Wire and Seale construction ropes are uniform in size. The fundamental difference between these types is that the layer of wires underneath the outside layer in the Seale type is made up of wires all of the same size. The wires under the outside layer of the Filler Wire rope are made up of a combination of main wires, each of the same size, and smaller filler wires, each of the same size, nested between the main wires. The outside layer of wires, therefore, is supported partly by the main inside wires and partly by the filler wires.

Some ropes have shaped or formed (triangular) wires to improve the wear and bearing properties of the outer layers (rather than circular drawn wire).

By having different lay directions of the strands and wire (left and right - also known as S and Z), it is possible to balance the torque value - resulting in a rope that does not tend to untwist when load is applied. This is called torque balanced or non-rotating rope.

Terminations

Right-hand ordinary lay (RHOL) wire rope terminated in a loop with a thimble and ferrule.

The end of a wire rope tends to fray readily, and cannot be easily connected to plant and equipment. There are different ways of securing the ends of wire ropes to prevent fraying. The most common and useful type of end fitting for a wire rope is to turn the end back to form a loop. The loose end is then fixed back on the wire rope. Termination efficiencies vary from about 70% for a Flemish eye alone; to nearly 90% for a Flemish eye and splice; to 100% for potted ends and swagings.

Thimbles

When the wire rope is terminated with a loop, there is a risk that it will bend too tightly, especially when the loop is connected to a device that spreads the load over a relatively small area. A thimble can be installed inside the loop to preserve the natural shape of the loop, and protect the cable from pinching and abrading on the inside of the loop. The use of thimbles in loops is industry best practice. The thimble prevents the load from coming into direct contact with the wires.

Wire rope clamps/clips

A wire rope clamp, also called a clip, is used to fix the loose end of the loop back to the wire rope. It usually consists of a u-shaped bolt, a forged saddle and two nuts. The two layers of wire rope are placed in the u-bolt. The saddle is then fitted over the ropes on to the bolt (the saddle includes two holes to fit to the u-bolt). The nuts secure the arrangement in place. Three or more clamps are usually used to terminate a wire rope. As many as eight may be needed for a 2 in (50.8 mm) diameter rope. There is an old adage which has over time became the rule; when installing clamps to secure the loop at the end of your wire rope make sure you do not "saddle a dead horse." The saddle portion of the clamp assembly is placed and tightened on the opposite side of the terminal end of the cable (the load bearing or live end). According to the US Navy Manual S9086-UU-STM-010, Chapter 613R3, Wire and Fiber Rope and Rigging, "This is to protect the live or stress-bearing end of the rope against crushing and abuse. The flat bearing seat and extended prongs of the body (saddle) are designed to protect the rope and are always placed against the live end." The US Navy and most regulatory bodies do not recommend the use of such clips as permanent terminations.

Swaged terminations

Swaging is a method of wire rope termination that refers to the installation technique. The purpose of swaging wire rope fittings is to connect two wire rope ends together, or to otherwise terminate one end of wire rope to something else. A mechanical or hydraulic swager is used to compress and deform the fitting, creating a permanent connection. There are many types of swaged fittings. Threaded Studs, Ferrules, Sockets, and Sleeves a few examples. Swaging ropes with fibre cores is not recommended.

Wedge Sockets

A wedge socket termination is useful when the fitting needs to be replaced frequently. For example, if the end of a wire rope is in a high-wear region, the rope may be periodically trimmed, requiring the termination hardware to be removed and reapplied. An example of this is on the ends of the drag ropes on a dragline. The end loop of the wire rope enters a tapered opening in the socket, wrapped around a separate component called the wedge. The arrangement is knocked in place, and load gradually eased onto the rope. As the load increases on the wire rope, the wedge become more secure, gripping the rope tighter.

Potted ends or Poured sockets

Poured sockets are used to make a high strength, permanent termination; they are created by inserting the wire rope into the narrow end of a conical cavity which is oriented in-line with the intended direction of strain. The individual wires are splayed out inside the cone, and the cone is then filled with molten zinc, or now more commonly, an epoxy resin compound.

Eye splice or Flemish eye

The ends of individual strands of this eye splice used aboard a cargo ship are served with natural fiber cord after the splicing is complete. This helps protect seaman's hands when handling.

An eye splice may be used to terminate the loose end of a wire rope when forming a loop. The strands of the end of a wire rope are unwound a certain distance, and plaited back into the wire rope, forming the loop, or an eye, called an eye splice. When this type of rope splice is used specifically on wire rope, it is called a "Molly Hogan", and, by some, a "Dutch" eye instead of a "Flemish" eye.

Codes and standards

Australia

The following Australian Standards apply to wire rope:

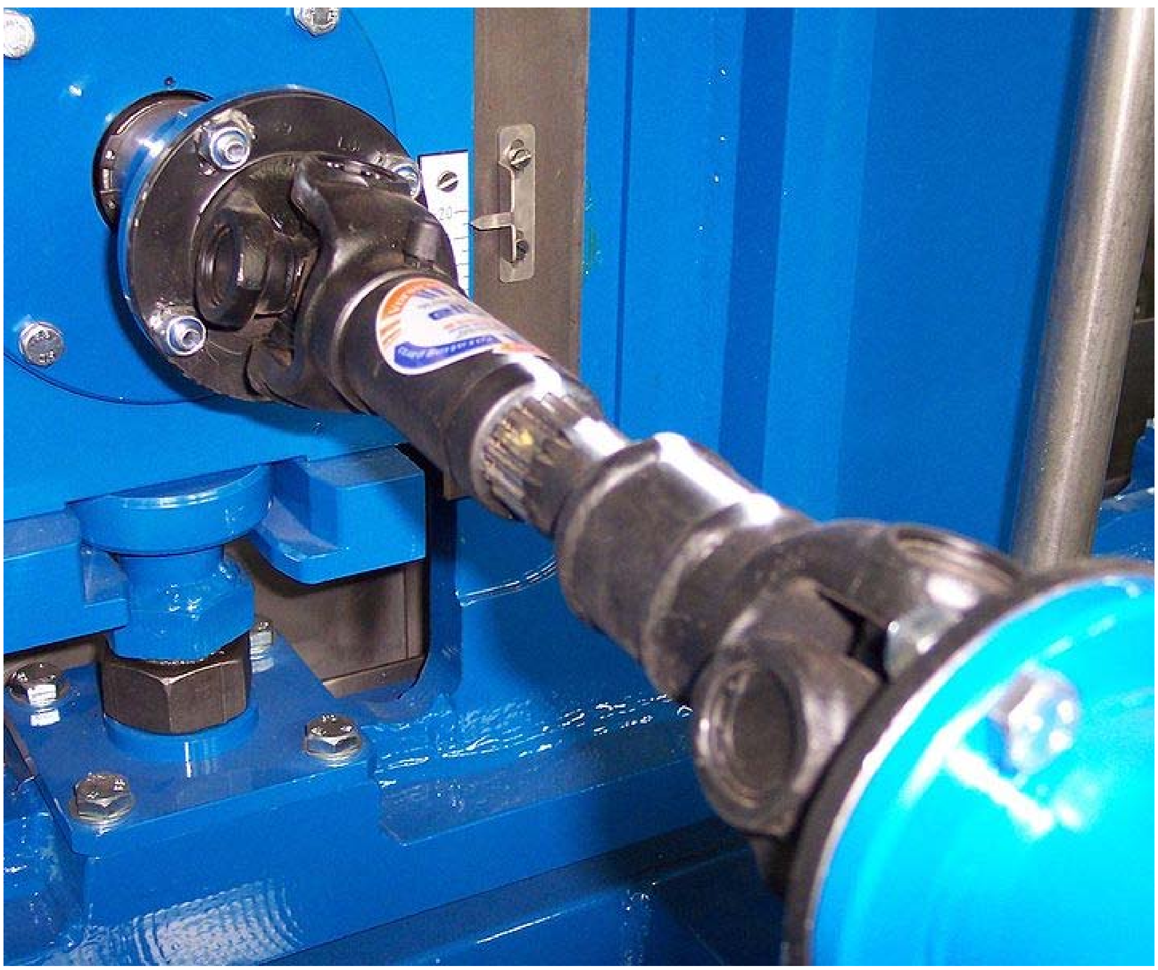
- AS 1138-1992 Thimbles for wire rope
- AS 1394-2001 Round steel wire for ropes
- AS 1666.1-1995 Wire-rope slings - Product specification
- AS 1666.2-1995 Wire-rope slings - Care and use
- AS 2076-1996 Wire-rope grips for non-lifting applications
- AS 2759-2004 Steel wire rope - Use, operation and maintenance
- AS 3569-1989 Steel wire ropes
- AS/NZS 4812-2003 Non-destructive examination and discard criteria for wire ropes in mine winding systems

The following EN Standards apply to wire rope:

The other Parts of EN 12385 are: Part 1: General requirements Part 2: Definitions, designation and classification Part 3: Information for use and maintenance Part 4: Stranded ropes for general lifting applications Part 5: Stranded ropes for lifts Part 6: Stranded ropes for mine shafts Part 7: Locked coil ropes for mine shafts Part 8: Stranded hauling and carrying-hauling ropes for cableway installations designed to carry persons Part 9: Locked coil carrying ropes for cableway installations designed to carry persons Part 10: Spiral ropes for general structural applications

Chapter 8

Drive Shaft



Drive shaft with universal joints at each end and a spline in the center

A **drive shaft**, **driveshaft**, **driving shaft**, **propeller shaft**, or **Cardan shaft** is a mechanical component for transmitting torque and rotation, usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them.

Drive shafts are carriers of torque: they are subject to torsion and shear stress, equivalent to the difference between the input torque and the load. They must therefore be strong enough to bear the stress, whilst avoiding too much additional weight as that would in turn increase their inertia.

Drive shafts frequently incorporate one or more universal joints or jaw couplings, and sometimes a splined joint or prismatic joint to allow for variations in the alignment and distance between the driving and driven components.

History

The term **drive shaft** first appeared during the mid 19^{th} century. In Storer's 1861 patent reissue for a planing and matching machine, the term is used to refer to the belt-driven shaft by which the machine is driven. The term is not used in his original patent. Another early use of the term occurs in the 1861 patent reissue for the Watkins and Bryson horse-drawn mowing machine. Here, the term refers to the shaft transmitting power from the machine's wheels to the gear train that works the cutting mechanism.

In the 1890s, the term began to be used in a manner closer to the modern sense. In 1891, for example, Battles referred to the shaft between the transmission and driving trucks of his Climax locomotive as the drive shaft, and Stillman referred to the shaft linking the crankshaft to the rear axle of his shaft-driven bicycle as a drive shaft. In 1899, Bukey used the term to describe the shaft transmitting power from the wheel to the driven machinery by a universal joint in his Horse-Power. In the same year, Clark described his Marine Velocipede using the term to refer to the gear-driven shaft transmitting power through a universal joint to the propeller shaft. Crompton used the term to refer to the shaft between the transmission of his steam-powered Motor Vehicle of 1903 and the driven axle.

Automotive drive shafts

Vehicles

An automobile may use a longitudinal shaft to deliver power from an engine/transmission to the other end of the vehicle before it goes to the wheels. A pair of short drive shafts is commonly used to send power from a central differential, transmission, or transaxle to the wheels.

A truck double propeller shaft

Front-engine, rear-wheel drive

In front-engined, rear-drive vehicles, a longer drive shaft is also required to send power the length of the vehicle. Two forms dominate: The torque tube with a single universal joint and the more common Hotchkiss drive with two or more joints. This system became known as *Système Panhard* after the automobile company Panhard et Levassor patented it.

Most of these vehicles have a clutch and gearbox (or transmission) mounted directly on the engine with a drive shaft leading to a final drive in the rear axle. When the vehicle is stationary, the drive shaft does not rotate. A few, mostly sports, cars seeking improved weight balance between front and rear, and most commonly Alfa Romeos or Porsche 924s, have instead used a rear-mounted transaxle. This places the clutch and transmission at the *rear* of the car and the drive shaft between them and the engine. In this case the drive shaft rotates continuously as long as the engine does, even when the car is stationary and out of gear.

Early automobiles often used chain drive or belt drive mechanisms rather than a drive shaft. Some used electrical generators and motors to transmit power to the wheels.

Front-wheel drive

In British English, the term "drive shaft" is restricted to a transverse shaft that transmits power to the wheels, especially the front wheels. A drive shaft connecting the gearbox to a rear differential is called a **propeller shaft**, or **prop-shaft**. A prop-shaft assembly consists of a propeller shaft, a slip joint and one or more universal joints. Where the engine and axles are separated from each other, as on four-wheel drive and rear-wheel drive vehicles, it is the propeller shaft that serves to transmit the drive force generated by the engine to the axles.

A drive shaft connecting a rear differential to a rear wheel may be called a **half shaft**. The name derives from the fact that two such shafts are required to form one rear axle.

Several different types of drive shaft are used in the automotive industry:

- One-piece drive shaft
- Two-piece drive shaft
- Slip-in-tube drive shaft

The slip-in-tube drive shaft is a new type that also helps in crash energy management. It can be compressed in the event of a crash, so is also known as a collapsible drive shaft.

Four wheel and all-wheel drive

These evolved from the front-engine rear-wheel drive layout. A new form of transmission called the transfer case was placed between transmission and final drives in both axles. This split the drive to the two axles and may also have included reduction gears, a dog clutch or differential. At least two drive shafts were used, one from the transfer case to each axle. In some larger vehicles, the transfer box was centrally mounted and was itself driven by a short drive shaft. In vehicles the size of a Land Rover, the drive shaft to the front axle is noticeably shorter and more steeply articulated than the rear shaft, making it a more difficult engineering problem to build a reliable drive shaft, and which may involve a more sophisticated form of universal joint.

Modern light cars with all-wheel drive (notably Audi or the Fiat Panda) may use a system that more closely resembles a front-wheel drive layout. The transmission and final drive for the front axle are combined into one housing alongside the engine, and a *single* drive shaft runs the length of the car to the rear axle. This is a favoured design where the torque is biased to the front wheels to give car-like handling, or where the maker wishes to produce both four-wheel drive and front-wheel drive cars with many shared components.

Drive shaft for Research and Development (R&D)

The automotive industry also uses drive shafts at testing plants. At an engine test stand a drive shaft is used to transfer a certain speed / torque from the Internal combustion engine to a dynamometer. A "shaft guard" is used at a shaft connection to protect against contact with the drive shaft and for detection of a shaft failure. At a transmission test stand a drive shaft connects the prime mover with the transmission.

Motorcycle drive shafts

A 1913 FN (Fabrique Nationale), Belgium, 4cylinders and shaft drive

A 1923 BMW R32, with a shaft-drive, boxer twin engine

Drive shafts have been used on motorcycles almost as long as there have been motorcycles. As an alternative to chain and belt drives, drive shafts offer relatively maintenance-free operation and long life. A disadvantage of shaft drive on a motorcycle is that gearing or a Hobson's joint or similar is needed to turn the power 90° from the shaft to the rear wheel, losing some power in the process. On the other hand, it is easier to protect the shaft linkages and drive gears from dust, sand and mud.

The best known motorcycle manufacturer to use shaft drive for a long time—since 1923—is BMW. Among contemporary manufacturers, Moto Guzzi is also well-known for its shaft drive motorcycles. The British company, Triumph and all four Japanese brands, Honda, Suzuki, Kawasaki and Yamaha, have produced shaft drive motorcycles. All geared models of the Vespa scooter produced to date have been shaft-driven. The automatic models, however, use a belt.

Motorcycle engines positioned such that the crankshaft is longitudinal and parallel to the frame are often used for shaft driven motorcycles. This requires only one 90° turn in power transmission, rather than two. Bikes from Moto Guzzi and BMW, plus the Triumph Rocket III and Honda ST series all use this engine layout.

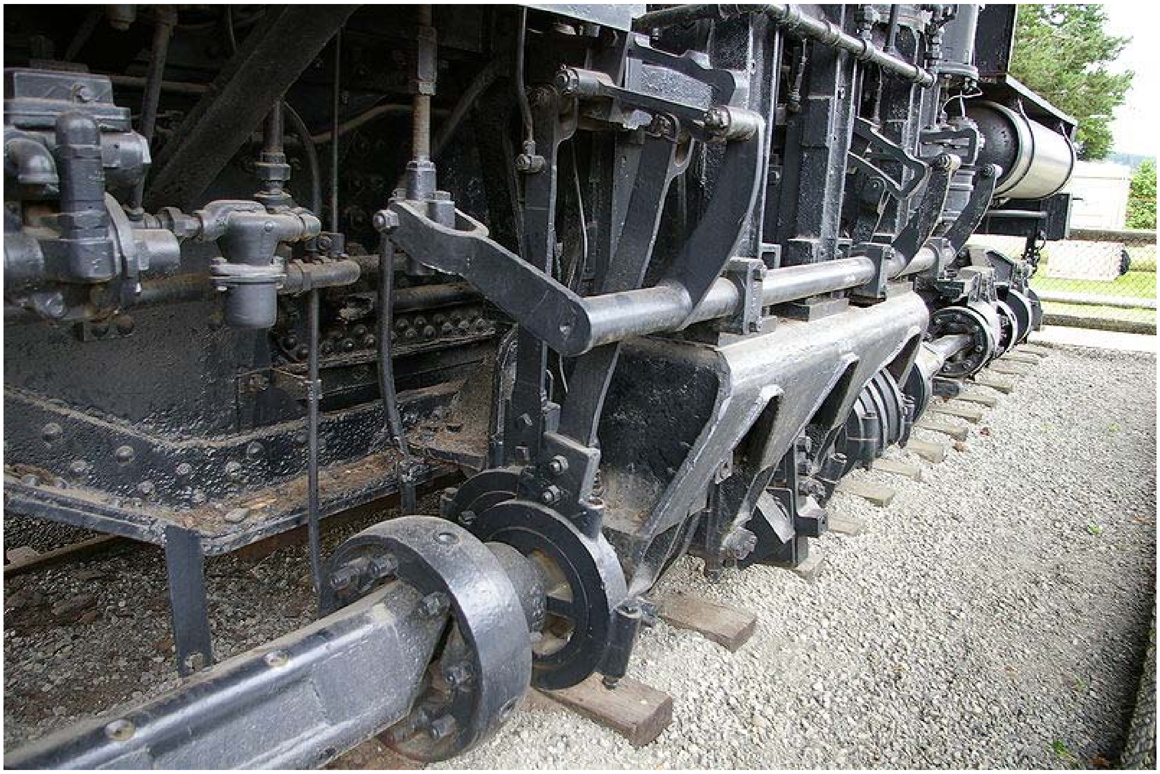
Motorcycles with shaft drive are subject to shaft effect where the chassis climbs when power is applied. This is counteracted with systems such as BMW's Paralever, Moto Guzzi's CARC and Kawasaki's Tetra Lever.

Marine drive shafts

On a power-driven ship, the drive shaft, or propeller shaft, usually connects the transmission inside the vessel directly to the propeller, passing through a stuffing box or other seal at the point it exits the hull. There is also a thrust block, a bearing to resist the axial force of the propeller. As the rotating propeller pushes the vessel forward, any length of drive shaft between propeller and thrust block is subject to compression, and when going astern to tension. Except for the very smallest of boats, this force isn't taken on the gearbox or engine directly.

Cardan shafts are also often used in marine applications between the transmission and either a propeller gearbox or waterjet.

Locomotive drive shafts



The rear drive shaft, crankshaft and front drive shaft of a Shay locomotive.

The Shay, Climax and Heisler locomotives, all introduced in the late 19th century, used quill drives to couple power from a centrally mounted multi-cylinder engine to each of the trucks supporting the engine. On each of these geared steam locomotives, one end of each drive shaft was coupled to the driven truck through a universal joint while the other end was powered by the crankshaft, transmission or another truck through a second universal joint. A quill drive also has the ability to slide lengthways, effectively varying its length. This is required to allow the bogies to rotate when passing a curve.

Cardan shafts are used in some diesel locomotives (mainly diesel-hydraulics, such as British Rail Class 52) and some electric locomotives (e.g. British Rail Class 91). They are also widely used in diesel multiple units.

Drive shafts in bicycles

A shaft-driven bicycle.

The drive shaft has served as an alternative to a chain-drive in bicycles for the past century, although never becoming very popular. A shaft-driven bicycle is described as an "Acatane", from one of their early makers. When used on a bicycle, a drive shaft has several advantages and disadvantages:

Advantages

- Drive system is less likely to become jammed, a common problem with chain-driven bicycles
- The rider cannot become dirtied from chain grease or injured by the chain from "Chain bite", which occurs when clothing or even a body part catches between the chain and a sprocket
- Lower maintenance than a chain system when the drive shaft is enclosed in a tube
- More consistent performance. Dynamic Bicycles claims that a drive shaft bicycle can deliver 94% efficiency, whereas a chain-driven bike can deliver anywhere from 75-97% efficiency based on condition
- Greater clearance: with the absence of a derailleur or other low-hanging machinery, the bicycle has nearly twice the ground clearance

Disadvantages

- A drive shaft system weighs more than a chain system, usually 1-2 pounds heavier
- At optimum upkeep, a chain delivers greater efficiency
- Many of the advantages claimed by drive shaft's proponents can be achieved on a chain-driven bicycle, such as covering the chain and gears with a metal or plastic cover
- Use of lightweight derailleur gears with a high number of ratios is impossible, although hub gears can be used
- Wheel removal can be complicated in some designs (as it is for some chain-driven bicycles with hub gears).

Chapter 9

Braking Chopper and DC Injection Braking

Braking chopper

A sample of a Braking chopper

Brake choppers are used in the DC voltage intermediate circuits of frequency converters to control voltage when the load feeds energy back to the intermediate circuit. This arises, for example, when a magnetized motor is being roatated by an overhauling load and so functions as a generator feeding power to the DC voltage intermediate circuit.

The concept of flux braking

Flux braking is a method based on motor losses. When braking in the drive system is needed, the motor flux and thus also the magnetizing current component used in the motor are increased. The control of flux can be easily achieved through the direct torque control principle. With DTC the inverter is directly controlled to achieve the desired torque and flux for the motor. During flux braking the motor is under DTC control which guarantees that braking can be made according to the specified speed ramp.This is very different to the DC injection braking typically used in drives. In the DC injection method DC current is injected to the motor so that control of the motor flux is lost during braking. The flux braking method based on DTC enables the motor to shift quickly from braking to motoring power when requested.

In flux braking the increased current means increased losses inside the motor. The braking power is therefore also increased although the braking power delivered to the frequency converter is not increased. The increased current generates increased losses in motor resistances. The higher the resistance value the higher the braking energy dissipation inside the motor. Typically, in low power motors(below 5 kW) the resistance value of the motor is relatively large in respect to the nominal current of the motor. The higher the power or the voltage of the motor the less the resistance value of the motor in respect to motor current. In other words, flux braking is most effective in a low power motor.

Functioning of braking chopper

A large Braking chopper being put to use

The other possibility to limit DC bus voltage is to lead the braking energy to a resistor through a braking chopper. The braking chopper is an electrical switch that connects DC bus voltage to a resistor where the braking energy is converted to heat. The braking choppers are automatically activated when the actual DC bus voltage exceeds a specified level depending on the nominal voltage of the Variable-frequency drive

Benefits of the braking chopper and resistor solutions

1. Simple electrical construction and well-known technology.
2. Low fundamental investment for chopper and resistor.
3. The chopper works even if AC supply is lost. Braking during main power loss may be required. E.g. in elevator or other safety related applications.

Drawbacks of the Braking chopper and resistor

1. The braking energy is wasted if the heated air can not be utilised.
2. The braking chopper and resistors require additional space.
3. May require extra investments in the cooling and heat recovery system.
4. Braking choppers are typically dimensioned for a certain cycle, e.g. 100 % power 1/10 minutes, long braking times require more accurate dimensioning of the braking chopper.
5. Increased risk of fire due to hot resistor and possible dust and chemical components in the ambient air space.
6. The increased DC bus voltage level during braking causes additional voltage stress on motor insulation.

When to apply a braking chopper

1. The braking cycle is needed occasionally.
2. The amount of braking energy with respect to motoring energy is extremely small.
3. Braking operation is needed during main power loss.

When not to use Braking Chopper Resistor

1. The braking is continuous or regularly repeated.
2. The total amount of braking energy is high in respect to the motoring energy needed.
3. The instantaneous braking power is high, e.g. several hundred kW for several minutes.
4. The ambient air includes substantial amounts of dust or other potentially combustible or explosive or metallic components.

DC injection braking

DC injection brake module

DC injection braking is a method of slowing AC electric motors. A DC voltage is injected into the winding of the AC motor after the AC voltage is disconnected, providing braking force to the rotor.

Applications of DC injection braking

When power is disconnected from the motor, the rotor spins freely until friction slows it to a stop. Large rotors and loads with a high moment of inertia may take a significant amount of time to stop through inherent friction alone. To reduce downtime, or possibly as an emergency safety feature, DC injection braking can be used to quickly stop the rotor.

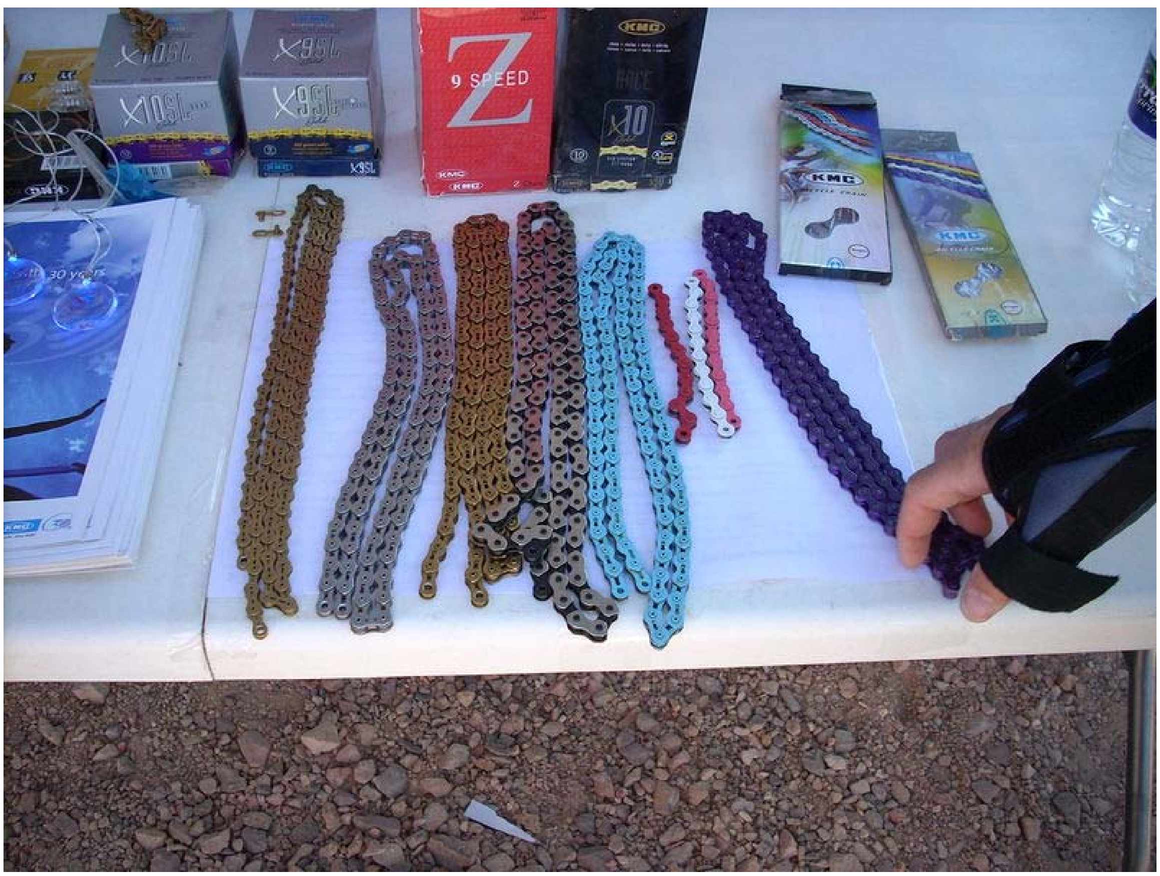
A DC injection brake system can be used as an alternative to a friction brake system. DC injection brakes only require a small module located with the other motor switchgear and/or drivers, mounted in a remote and convenient location, whereas a friction brake must be mounted somewhere on the rotating system. Friction brakes eventually wear out with use and require replacement of braking components. DC brake modules do not have consumable parts and should not require maintenance. Friction brakes also require a method of actuation, requiring either a human operator or system controlled actuator, adding to the complexity of the system. A DC brake is easily integrated into the motor control circuitry.

Operation

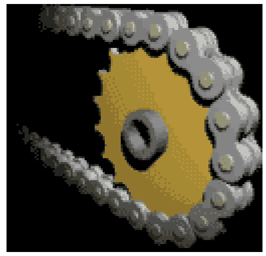
A DC voltage is applied to the motor windings, creating a stationary magnetic field which applies a static torque to the rotor. This slows and eventually halts the rotor completely. As long as the DC voltage is applied to the windings, the rotor will be held in position and resistant to any attempt to spin it. The higher the voltage that is applied, the stronger the braking force and holding power.

Chapter 10

Bicycle Chain



Bicycle chains



Roller chain and sprocket

A **bicycle chain** is a roller chain that transfers power from the pedals to the drive-wheel of a bicycle, thus propelling it. Most bicycle chains are made from plain carbon or alloy steel, but some are chrome-plated or stainless steel to prevent rust, or simply for aesthetics.

History

Obsolete chain designs previously used on bicycles included the block chain, the skip-link chain, and the Simpson lever chain. Most modern bicycle chains used with a single chainring and single rear sprocket are conventional industrial bushing chain. Until the 1980s, most derailleur chains were also bushing chains, but today, virtually all derailleur chains are of the "Sedis" bushingless design. Compared to a bushing chain, a bushingless chain is cheaper to make, is less likely to break under shifting load, promotes better lubricant flow inside the rollers, and creates more lateral flexibility for multi-geared bicycles. However, it also wears much faster and has slightly worse mechanical efficiency than a bushing chain.

Before the safety bicycle, bicycles did not have chains and the pedals were typically attached directly to the drive-wheel, thus limiting top speed by the diameter of the wheel and resulting in designs with front wheels as large as possible. Various linkage mechanisms were invented to raise the effective gear ratio, but with limited success. Using chain drive allowed the mechanical advantage between the drive and driven sprockets to determine the maximum speed, thereby enabling manufacturers to reduce the size of the driving wheel for safety. It also allowed for the development of variable gearing, allowing cyclists to adjust their gearing to the difficulty of the terrain, on the fly.

Efficiency

A bicycle chain can be very efficient: one study reported efficiencies as high as 98.6%. The study, performed in a clean laboratory environment, found that efficiency was not greatly affected by the state of lubrication. A larger sprocket will give a more efficient drive, reducing the movement angle of the links. Higher chain tension was found to be more efficient: "This is actually not in the direction you'd expect, based simply on friction".

Maintenance

Close-up of a utility bicycle's chain protected by a chain guard

How best to lubricate a bicycle chain is a commonly debated question among cyclists. Liquid lubricants penetrate to the inside of the links and are not easily displaced, but quickly attract dirt. "Dry" lubricants, often containing wax or Teflon, are transported by an evaporating solvent, and stay cleaner in use. The cardinal rule for long chain life is never to lubricate a dirty chain, as this washes abrasive particles into the rollers. Chains should be cleaned before lubrication. The chain should be wiped dry after the lubricant has had enough time to penetrate the links. An alternative approach is to change the (relatively cheap) chain very frequently; then proper care is less important. Some utility bicycles have fully-enclosing chain guards which virtually eliminate chain wear and maintenance. On recumbent bicycles the chain is often run through tubes to prevent it from picking up dirt, and to keep the cyclist's leg free from oil and dirt.

Removal

On most upright bicycles, the chain loops through the right rear triangle made by the right chain stay, right seat stay, and seat tube. Thus a chain must be separated, "broken" is a term commonly used, with a chain tool or at a master link. A master link, also known as a connecting link, allows the chain to be inserted or removed with simpler tools, or even no tools, for cleaning or replacement.

Some newer chain designs, such as Shimano and Campagnolo 10-speed chains, require a special replacement pin to be used when installing or reinstalling a separated chain. An alternative to this process is to install a master link, such as a SRAM Power Link or a Wipperman Connex.

Wear

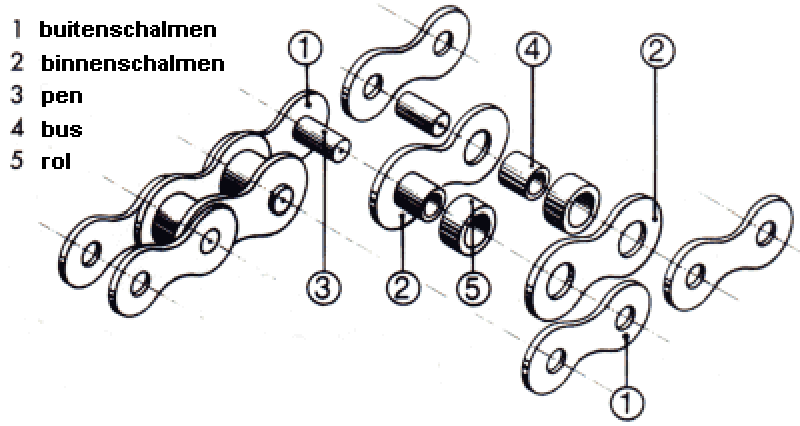
Chain wear, or chain stretch, becomes an issue with extensive cycling. Although the overall effect is often called "stretch", chains generally wear through attrition of the bushings (or half-bushings, in the Sedis design) and **not** by elongation of the sideplates. The tension created by pedaling is insufficient to cause the latter. Because an old chain is longer than needed, its links will not precisely fit the spaces between teeth in the drivetrain, making gear shifts a problem and possibly resulting in a 'skipping' chain that reduces power transfer and makes pedalling very uncomfortable.

Since chain wear is strongly aggravated by dirt getting into the links, the *lifetime* of a chain depends mostly on how well it is cleaned (and lubricated) and does not depend on the mechanical load. Therefore, well-groomed chains of heavily used racing bicycles will often last much longer than those of a lightly used, but not so well cleaned city bike. Depending on use and cleaning, a chain can last only 1,000 km (e.g. in cross-country use, or all-weather abuse), 3,000 to 5,000 km for well-maintained derailer chains, or more than 6,000 km for perfectly groomed high-quality chains, single-gear, or hub-gear chains (preferably with a full cover chain guard).

Chain wear rates are highly variable, so replacement by calendar is likely to cause either needless chain replacement or continued use of a worn chain, damaging rear sprockets. One way to measure wear is with a ruler. Another is with a chain wear tool, which typically has a "tooth" of about the same size found on a sprocket. They are simply placed on a chain under light load and report a "go/no-go" result - if the tooth drops in all the way, the chain should be replaced.

Twenty half-links in a new chain measure 10" (254 mm), and replacement is recommended before the old chain measures 256 mm (0.7% wear). A safer time to replace a chain is when 24 half-links in the old chain measure $12^1/_{16}$ inches (0.5% wear). If the chain has worn beyond this limit, the rear sprockets are also likely to wear, in extreme cases followed by the front chainrings. In this case, the 'skipping' mentioned above is liable to continue even after the chain is replaced, as the teeth of the sprockets will have become unevenly worn (in extreme cases, hook-shaped). Replacing worn sprocket cassettes and chainrings after missing the chain replacement window is much more expensive than simply replacing a worn chain in the first place.

Sizes



Exploded view of a few bicycle chain links

The chain in use on modern bicycles has a 1/2" pitch, which is ANSI standard #40, where the 4 indicates the pitch of the chain in eighths of an inch, and metric #8, where the 8 indicates the pitch in sixteenths of an inch.

Width

Chain comes in either 3/32", 1/8", 5/32" or 3/16" roller widths: 5/32" is used on cargo bikes and trikes, 1/8" with the common low cost coaster (back pedal brake) bike, hub and fixed gearing and on track bicycles, and 3/32" with the derailleur gears most commonly fitted on racing, touring and mountain bikes.

Length

New chains usually come in a stock length, long enough for most upright bike applications. The appropriate number of links must be removed before installation in order for the drive train to function properly. The pin connecting links can be pushed out with a chain tool to shorten, and additional links may be added to lengthen.

In the case of derailleur gears the chain is usually long enough so that it can be shifted onto the largest front chain ring and the largest rear cog without jamming, and not so long that, when shifted onto the smallest front chain ring and the smallest rear cog, the rear derailleur cannot take up all the slack. Meeting both these requirements is only possible if the rear derailleur is compatible with the gear range being used on the bike.

In the case of single-speed bicycles and hub gears, the chain length must match the distance between crank and rear hub and the sizes of the front chain ring and rear cog. These bikes usually have some mechanism for small adjustments such as horizontal dropouts, track ends, or an eccentric mechanism in the rear hub or the bottom bracket. In extreme cases, a chain half-link may be necessary.

Variations

In order to reduce weight, chains have been manufactured with hollow pins and with cut-outs in the links. A few titanium chains have also been made, but while much lighter they are vastly more expensive, perhaps 10x the cost, and the titanium bearing surfaces reportedly wear quickly, leading to shortened life and reduced efficiency.

Manufacturers

Bicycle chains are made by companies such as:

- Campagnolo
- D.I.D.
- Izumi Chain MFG.
- KMC
- Rohloff AG
- Shimano
- SRAM
- Wippermann
- Yaban

Chapter 11

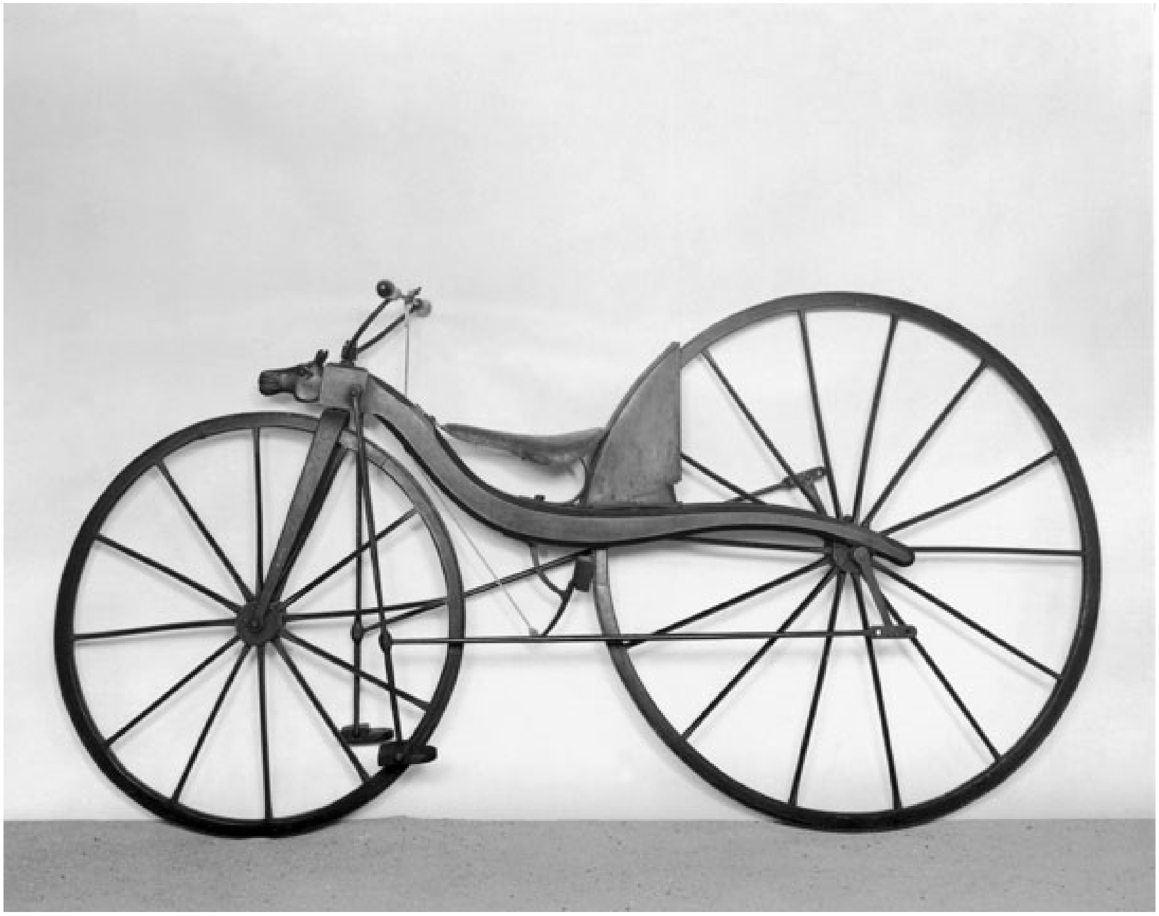
Bicycle Drivetrain Systems

A shaft-drive with crankset and rear gear hub

A rear derailleur

Bicycle drivetrain systems are used to transmit power on bicycles, tricycles, quadracycles, unicycles, or other human-powered vehicles from the riders to the drive wheels. Most also include some type of a mechanism to convert speed and torque via gear ratios.

History



A treadle bicycle

The history of bicycle drivetrain systems is closely linked to the history of the bicycle. Major changes in bicycle form have often been initiated or accompanied by advances in drivetrain systems. Several early drivetrains used straight-cut gears that meshed directly with each other outside of the hub. Some bicycles have used a double-sided rear wheel, with different-sized sprockets on each side. To change gears, the rider would stop and dismount, remove the rear wheel and reinstall it in the reverse direction. Derailleur systems were first developed in the late 19th century, but the modern cable-operated parallelogram derailleur was invented in the 1950s.

- Draisine
- Penny-farthing
- Safety bicycle

Power collection

A rowbike

Bicycle drivetrain systems have been developed to collect power from riders by a variety of methods.

From legs

- Crankset and pedals
- Treadle bicycle
- Vertical foot motion that mimicks that of a climbing exercise machine
- Elliptical foot motion that mimicks that of an elliptical trainer

From arms

- Handcycle

From whole body

- Rowing
- Hand and foot

From multiple riders

- Tandem bicycle
- Conference Bike

Power transmission

A belt-drive crankset

Bicycle drivetrain systems have been developed to transmit power from riders to drive wheels by a variety of methods. Most bicycle drivetrain systems incorporate a freewheel to allow coasting, but direct drive and fixed-gear systems do not. The later are sometimes also described as bicycle brake systems.

Direct

Some human powered vehicles, both historical and modern, employ direct drive. Examples include most Penny-farthings, unicycles, and children's tricycles.

Rotating

- Chain
- Chainless
    - Belt
    - Shaft
    - Wire rope as in the Stringbike and Rowbike

Non-rotating

- Hydraulic

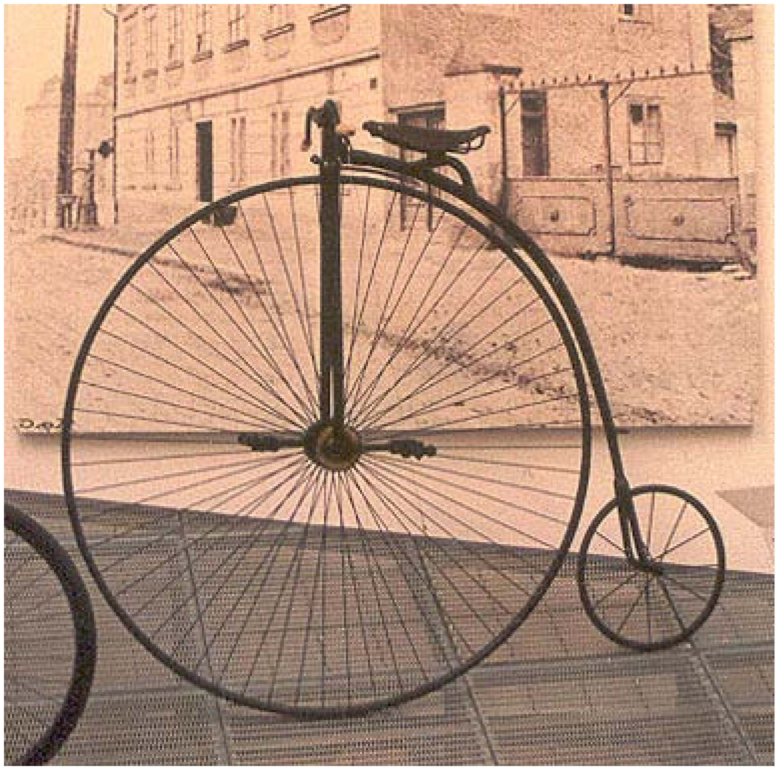
Two-wheel drive

Steve Christini and Mike Dunn introduced a two-wheel drive option. Their AWD system, aimed at mountain bikers, comprises an adapted differential that sends power to the front wheel once the rear begins to slip.

Speed and torque conversion

1888 Geared Facile Bicycle in the Coventry Transport Museum

A chain-drive and rear gear hub



A penny-farthing with direct drive

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. Bicycle drivetrain systems have been developed to convert speed and torque by a variety of methods.

Implementation

Several technologies have been developed to alter gear ratios. They can be used individually, as an external derailleur or an internal hub gear, or in combinations such as the SRAM DualDrive system, which uses a standard 8 or 9-speed cassette mounted on a three-speed internally-geared hub, offering a similar gear range as a bicycle with a cassette and triple chainrings.

- Derailleur gears
    - Cogset
    - Crankset
- Hub gear
    - Continuously variable
- Retro-Direct
- Lever and cam mechanism, as in the Stringbike

Control

- Shifters
    - Electronic Gear-Shifting System

Theory

- Bicycle gearing
    - Gear ratio
    - Gear inches

Single-speed

- Single-speed bicycle
    - Fixed-gear bicycle

Integration

While several combinations of power collection, transmission, and conversion exist, not all combinations are feasible. For example, a shaft-drive is usually accompanied by a hub gear, and derailleurs are usually implemented with chain drive.

Chapter 12

Key (Engineering)

In mechanical engineering, a **key** is a machine element used to connect a rotating machine element to a shaft. Through this connection the key prevents relative rotation between the two parts and allows torque to be transmitted through. For a key to function the shaft and rotating machine element must have a **keyway**, also known as a **keyseat**, which is a slot or pocket for the key to fit in. The whole system is called a **keyed joint**. A keyed joint still allows relative axial movement between the parts.

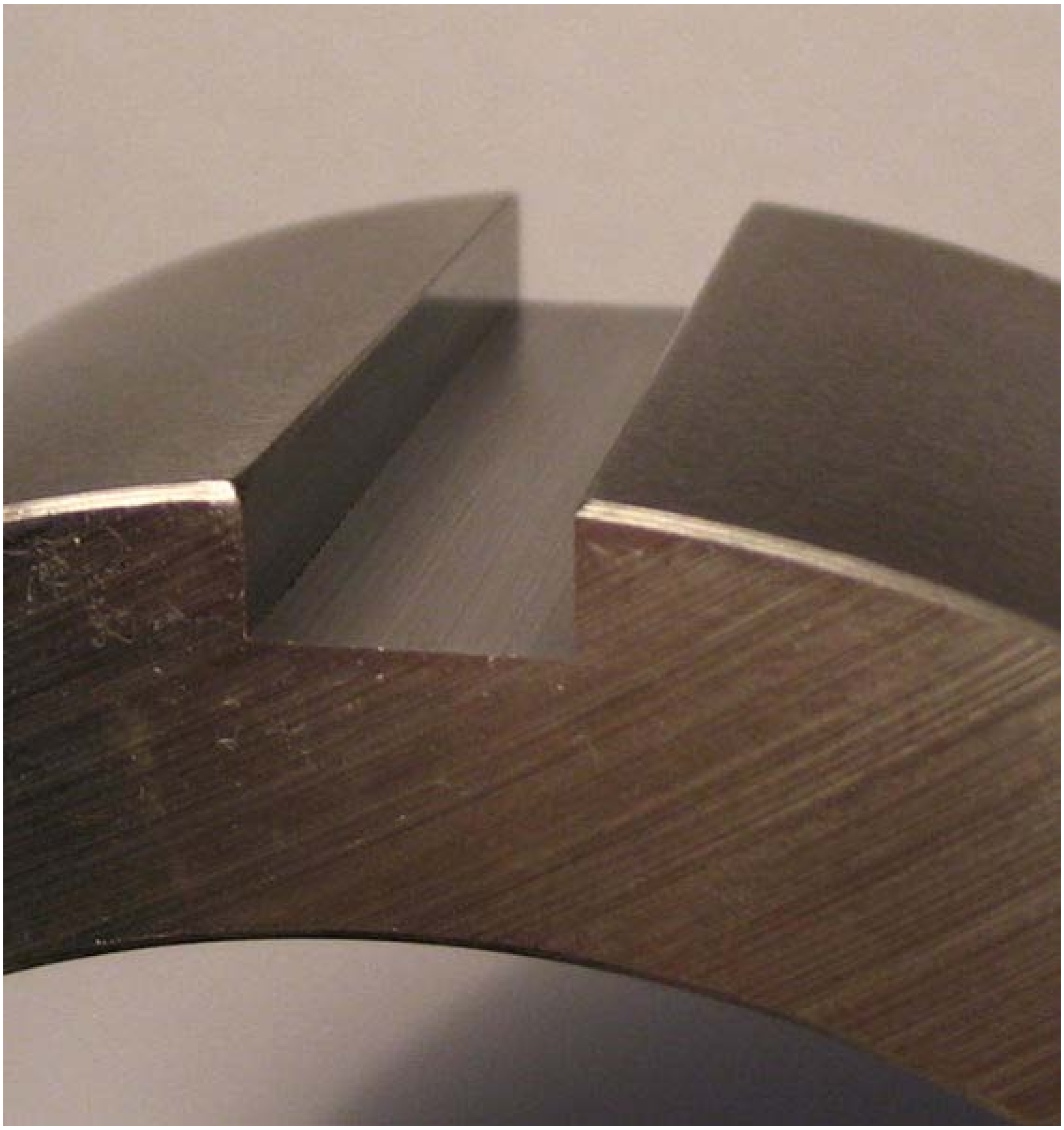
Commonly keyed components include gears, pulleys, and couplings.

Types

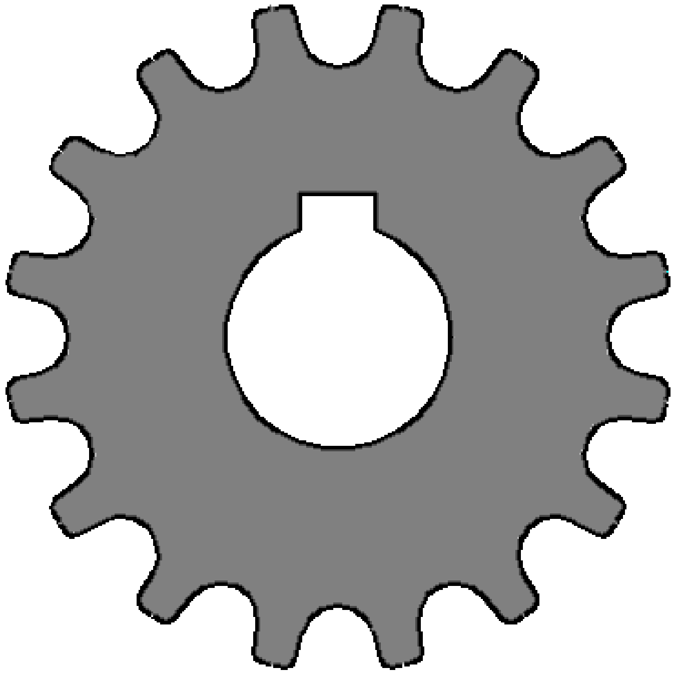
There are three main types of keys: *parallel*, *Woodruff*, and *tapered* keys.

Parallel keys

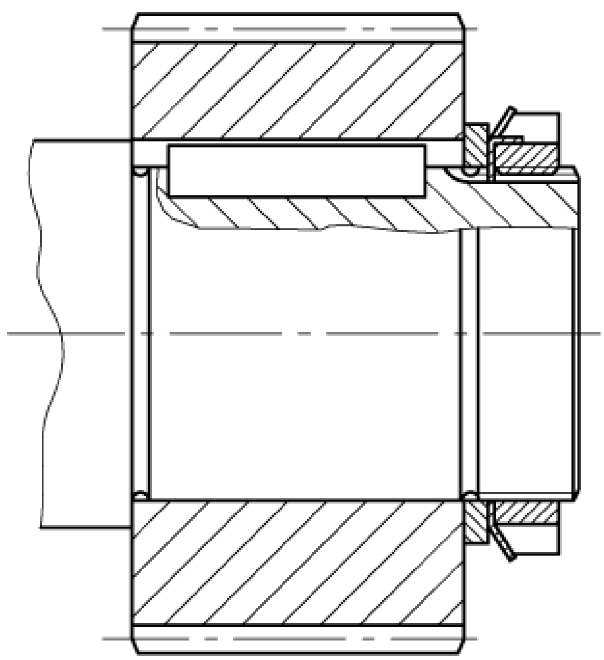
Parallel keys are the most widely used. They have a square or rectangular cross-section. Square keys are used for smaller shafts and rectangular faced keys are used for shaft diameters over 6.5 in (170 mm). Set screws often accompany parallel keys to lock the mating parts into place so they do not move. The keyway is a longitudinal slot in both the shaft and mating part.



The keyway in a shaft for a parallel key



A sprocket with an internal parallel keyway



Cross-section of a parallel keyed joint

Woodruff keys

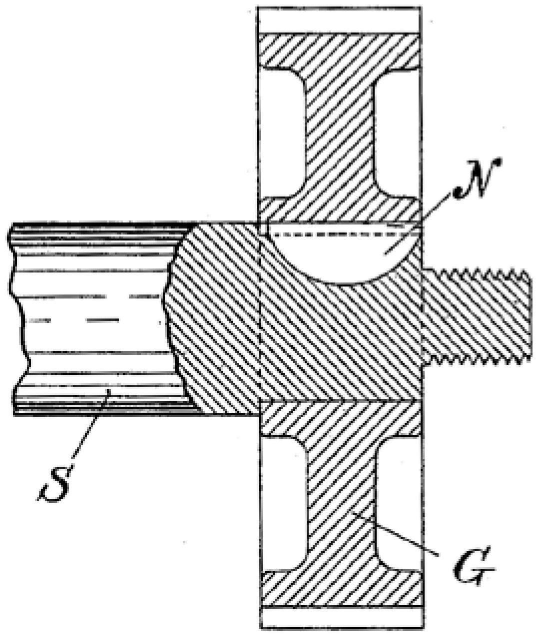
Woodruff keys, also known as *half-moon keys*, are semicircular shaped keys that, when installed, leave a protruding tab. The keyway in the shaft is a semi-circular pocket and the mating part has a longitudinal slot. They are used to improve the concentricity of the shaft and the mating part, which is critical for high speed operations. The main advantage of the Woodruff key is that avoids the milling of a keyway near shaft shoulders, which already have stress concentrations.

Common applications include machine tools, automotive applications, snowblowers and marine propellers.

This type of key was developed by W.N. Woodruff of Connecticut, who was presented in 1888 with the John Scott Medal by the Franklin Institute for the invention.

A Woodruff key installed

A Woodruff key and keyway



Gear G is held on shaft S by Woodruff key N

Tapered keys

The final type of key is the tapered key, which is tapered on one side, the side that engages the hub. The keyway in the hub is broached with a taper matching that of the tapered key. Some taper keys have a *gib*, or tab, for easier removal during disassembly. The purpose of the taper is to secure the key itself as well as to firmly engage the shaft to the hub without the use of a set screw. The problem with taper keys is that they can change the center of rotation of the shaft to be slightly off of the mating part.

Others

A "Scotch key" also provides a keyway not by milling but by drilling axially into the part and the shaft, so that a round key can be used.

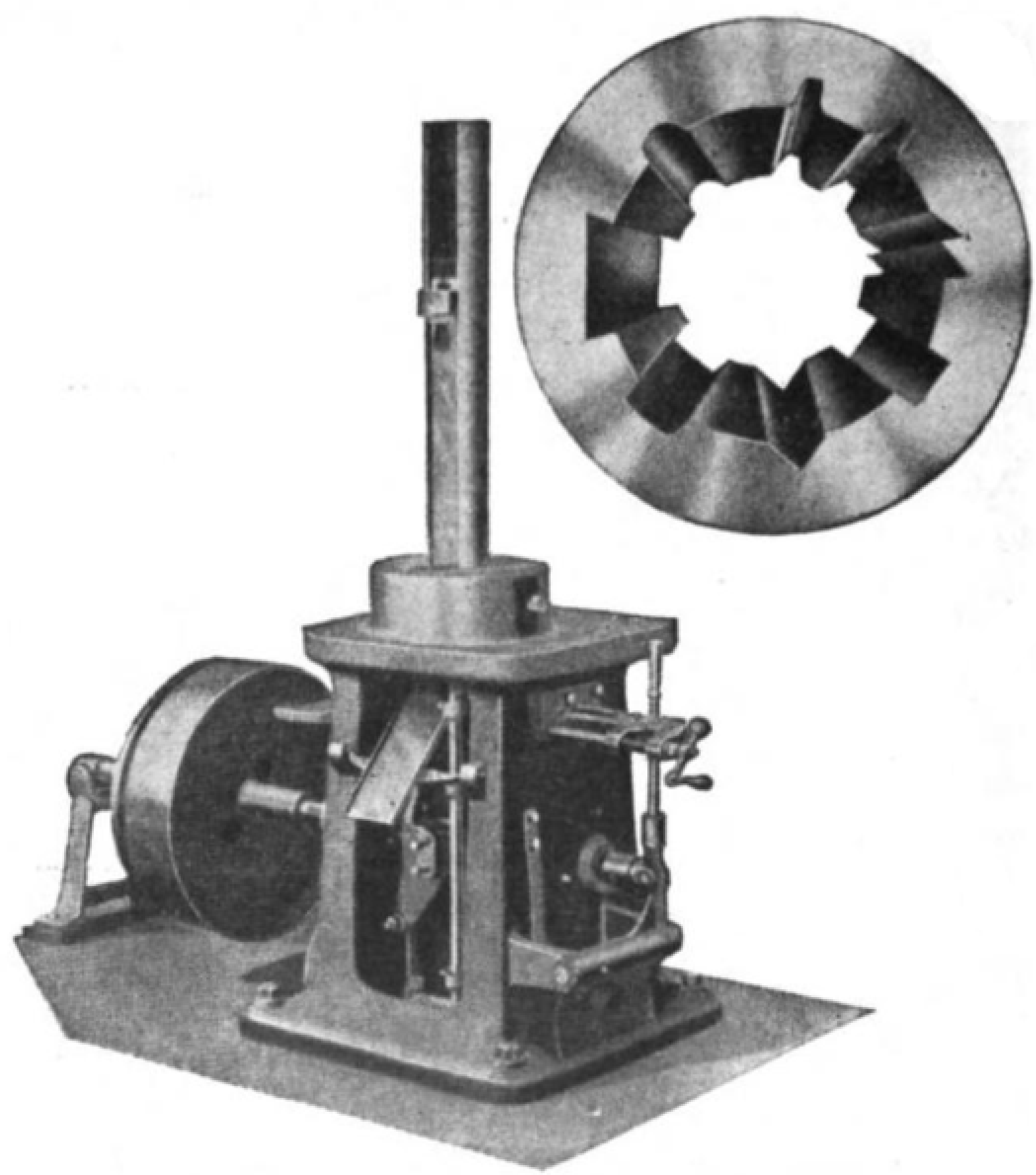
Keyseating

Keyseating is the creation of the slots in the mating items. Keyseating can be done on a variety of different machines including a keyseater, a broacher, either a vertical or horizontal mill, or with a chisel and file.

Broaching

Broaching primarily used to cut square cornered internal keyways. The specific broach, bushing and guide are used for each given keyway cross-section, which makes this process more expensive than most of the alternatives. However, it can produce the most accurate keyway out of all the processes. There are three main steps in broaching a keyway: First, the workpiece is set on the arbor press and the bushing is placed in the opening of the workpiece. Next, the broach is inserted and pushed through, cutting the keyway. Finally, shims are placed between the bushing and the broach to achieve the correct depth necessary for the key.

Keyseater



A keyseater and a sample of various shapes that can be cut

Keyseaters, also known as *keyseating machines* and *keyway cutters*, are specialized machines designed to cut keyways. They are very similar to vertical shapers; the difference is that the cutting tool on a keyseater enters the workpiece from the bottom and cuts on the down-stroke, while the tool on a shaper enters the workpiece from the top and cuts downward. Another difference is a keyseater has a guiding system above the workpiece to minimize deflection, which results in a closer tolerance cut. The process starts by clamping the workpiece to the table with a fixture or vise. The workpiece is properly located and then the reciprocating arm is started. Some models have a stationary table so the cutter is fed horizontally into the workpiece, while others have a movable table that feeds the workpiece into a fixed cutter. These machines can cut other straight sided features other than keyways. They can also produce blind slots, which are slots that do not extend through the whole workpiece.

Milling

Parallel, tapered, and Woodruff keyways can be produced on a milling machine. End mills or slotting cutters are used for parallel and tapered keyways, while a Woodruff cutter is used for Woodruff keyways.

For internal keyways that are not too long, the keyways can be milled if a radius is acceptable.

Chiseling

One of the earliest forms of keyseating was done by chiseling. The keyway is roughed out using a chisel and then filed to size; the key is tried frequently to avoid over filing. This technique is long, tedious, and rarely used anymore.

Keyed joints

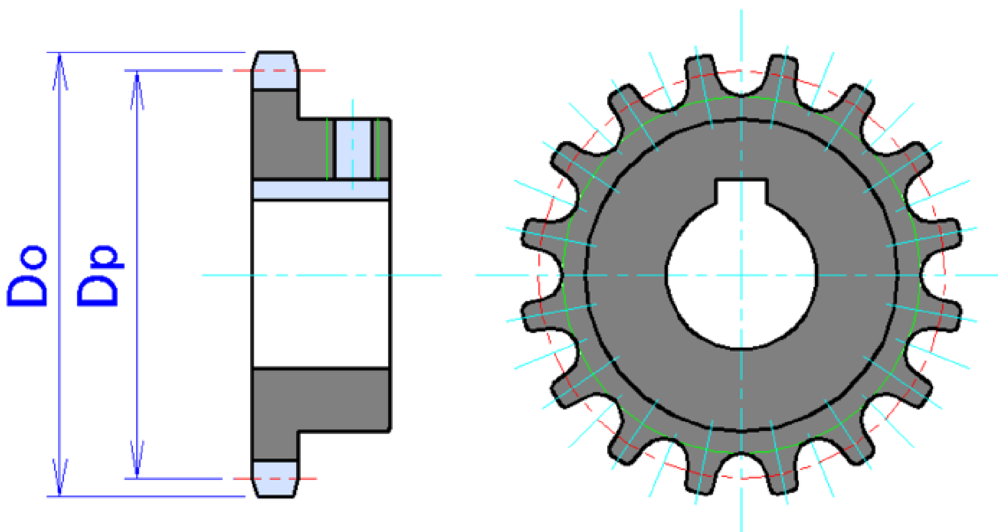
Two parallel keys can be used either 90° or 180° apart from each other if the shaft connection needs to be more robust.

Improperly machined keyways that had cutter deflection or drifting occur, may not be strong enough for the required application.

Chapter 13

Sprocket and Spline (Mechanical)

Sprocket



16T type sprocket
Do: Sprocket diameter
Dp: Pitch diameter

A **sprocket** is a profiled wheel with teeth that meshes with a chain, track or other perforated or indented material. It is distinguished from a gear in that sprockets are never meshed together directly, and differs from a pulley in that sprockets have teeth and pulleys are smooth.

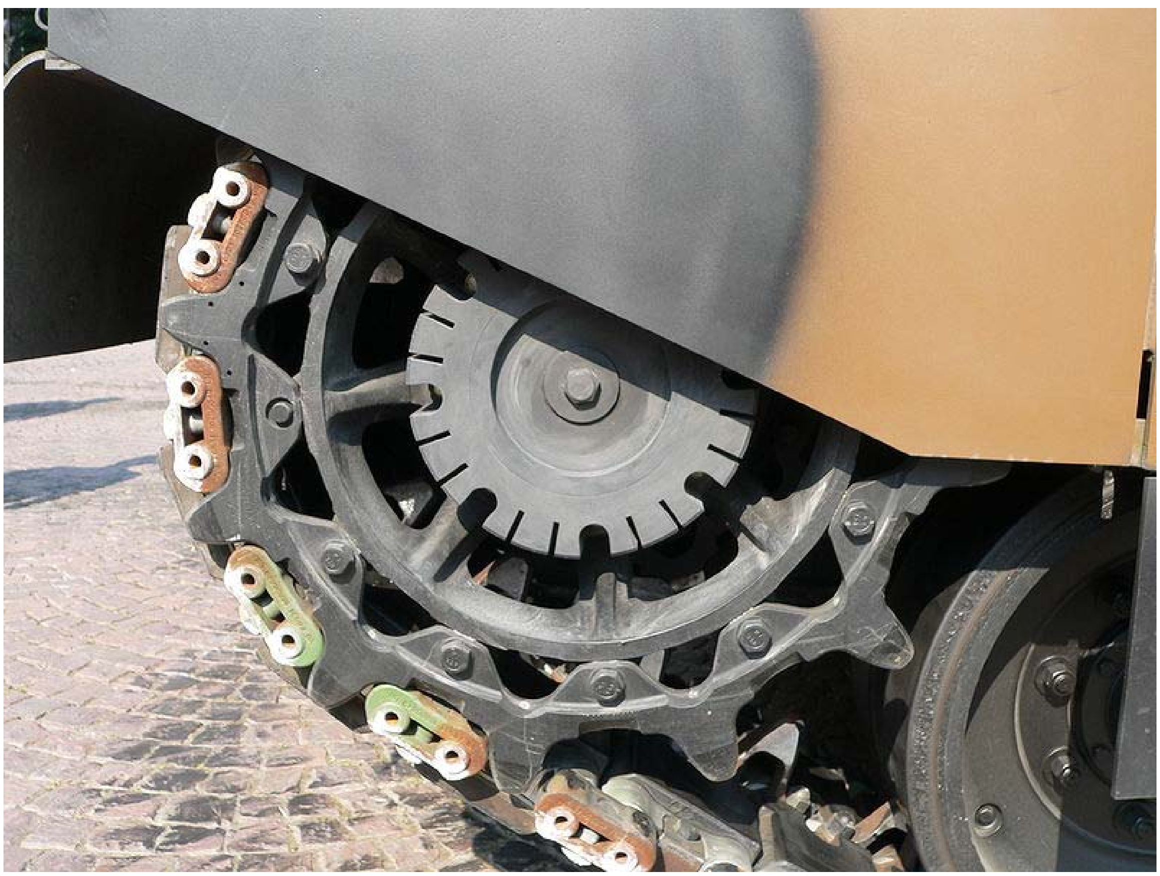
Sprockets are used in bicycles, motorcycles, cars, tracked vehicles, and other machinery either to transmit rotary motion between two shafts where gears are unsuitable or to impart linear motion to a track, tape etc.

Sprockets typically do not have a flange. Some sprockets used with timing belts have flanges to keep the timing belt centered.

Cycles

In the case of bicycle chains, it is possible to modify the overall gear ratio of the chain drive by varying the diameter (and therefore, the tooth count) of the sprockets on each side of the chain. This is the basis of Derailleur gears. A 10-speed bicycle, by providing two different-sized driving sprockets and five different-sized driven sprockets, allows up to ten different gear ratios. The resulting lower gear ratios make the bike easier to pedal up hills while the higher gear ratios make the bike faster to pedal on flat roads. In a similar way, manually changing the sprockets on a motorcycle can change the characteristics of acceleration and top speed by modifying the final drive gear ratio.

Tracked vehicles



A tank sprocket

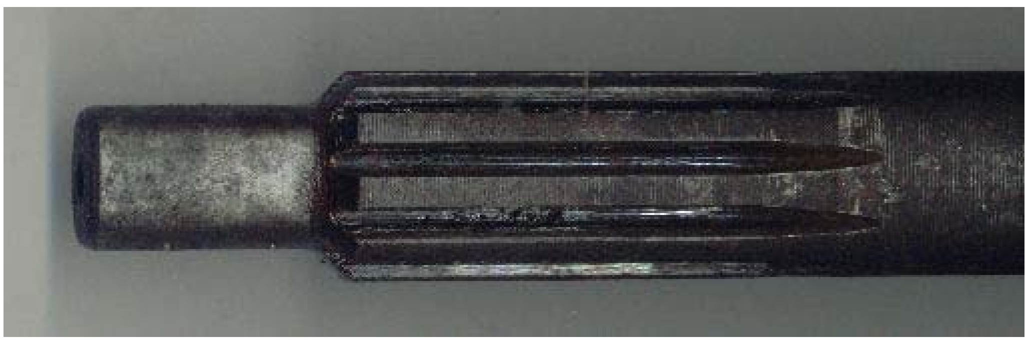
In the case of vehicles with caterpillar tracks the engine-driven toothed-wheel transmitting motion to the tracks is known as the *drive sprocket* and may be positioned at the front or back of the vehicle, or in some cases, both. There may also be a third sprocket, elevated, driving the track.

Film and paper

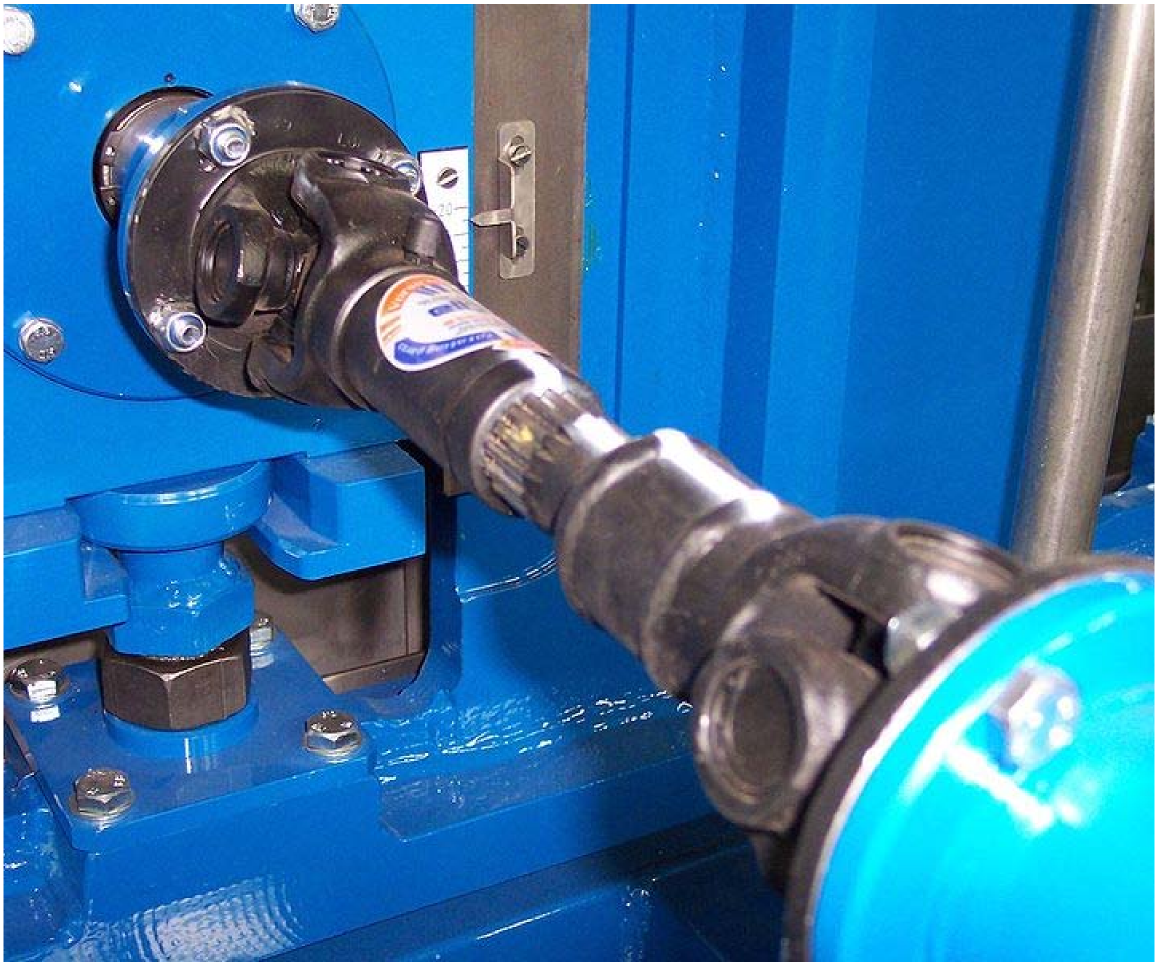
Sprockets are used in the film transport mechanisms of movie projectors and movie cameras. In this case, the sprocket wheels engage film perforations in the film stock.

Sprocket feed was also used for punched tape and is used for paper feed to some computer printers.

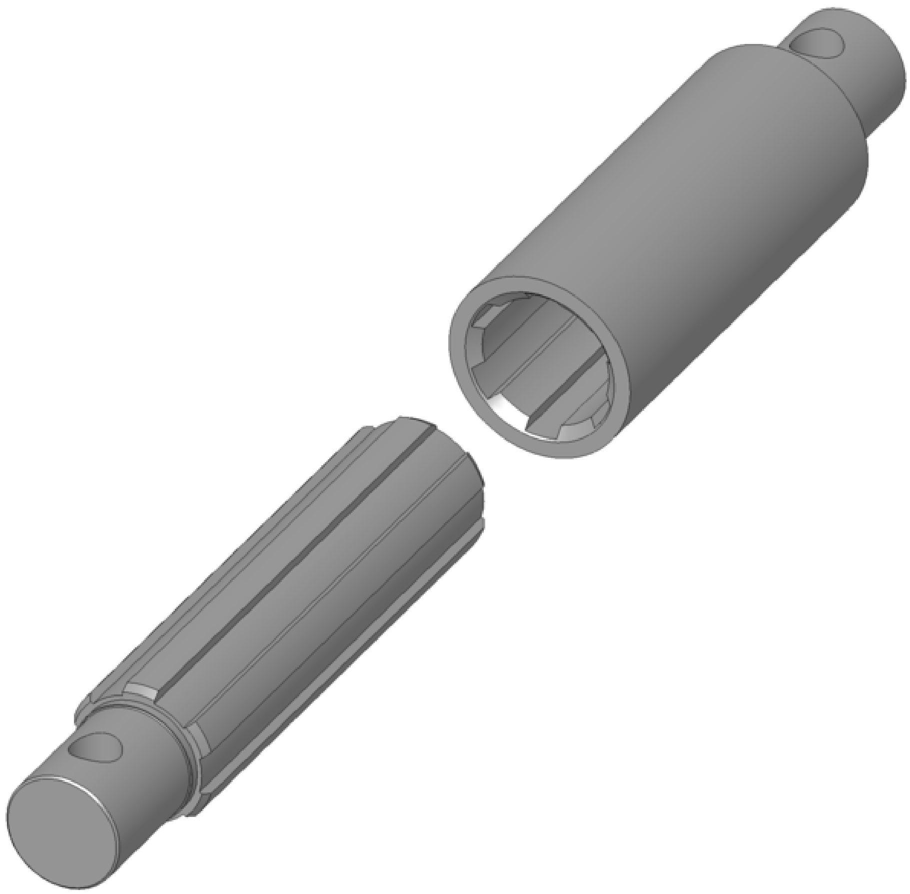
Spline



A spline on the end of a manual transmission input shaft



A drive shaft with a spline in the center to transmit torque and rotation and allow for changes in length



Detail of a spline joint

Splines on the end of a transaxle

Matching splines of a bicycle cassette and freehub with a master spline visible at the top

A **rotating spline** is a series of ridges, called splines or teeth, on a drive shaft that mesh with grooves in a mating piece and transfer torque to it, maintaining the angular correspondence between them. For instance, a gear mounted on a shaft might use a male spline on the shaft that matches the female spline on the gear. An alternative to splines is a keyway and key, though splines provide a longer fatigue life.

Types

There are several types of splines:

Parallel key spline
: where the sides of the equally-spaced grooves are parallel in both directions, radial and axial.

Involute spline
: where the sides of the equally-spaced grooves are involute, as with an involute gear, but not as tall. The curves increase strength by decreasing stress concentrations.

Crowned splines
: where the sides of the equally-spaced grooves are usually involute, but the male teeth are modified to allow for misalignment.

Serrations
: where the sides of the equally-spaced grooves form a "V". These are used on small-diameter shafts.

Helical splines
: where the equally-spaced grooves form a helix about the shaft. The sides may be parallel or involute. This can either minimize stress concentrations for a stationary joint under high load, or allow for rotary and linear motion between the parts.

Ball splines
: where the 'teeth' of the outer part are implemented with a ball bearing to allow for free linear motion even under high torque.

Uses

Drive shafts on vehicles and power take-offs use splines to transmit torque and rotation and allow for changes in length.

Splines are used in several places on bicycles. The crank arm to BB shaft interfaces that are splined include ISIS Drive, Truvativ GXP and Howitzer, Shimano's Octalink and many others, most of which are proprietary. Some cranksets feature modular spiders, where torque is transmitted through splines. Cassettes engage the freehub via a spline that has one groove wider than the others to enforce a fixed orientation. Disc brake mounting interfaces that are splined include Centerlock, by Shimano.

Aircraft engines may have a spline upon which mounts the propeller. There may be a master spline which is wider than the others, so that the propeller may go on at only one orientation, to maintain dynamic balance. This arrangement is commonly found in larger engines, where smaller engines typically use a pattern of threaded fasteners instead.

Manufacturing

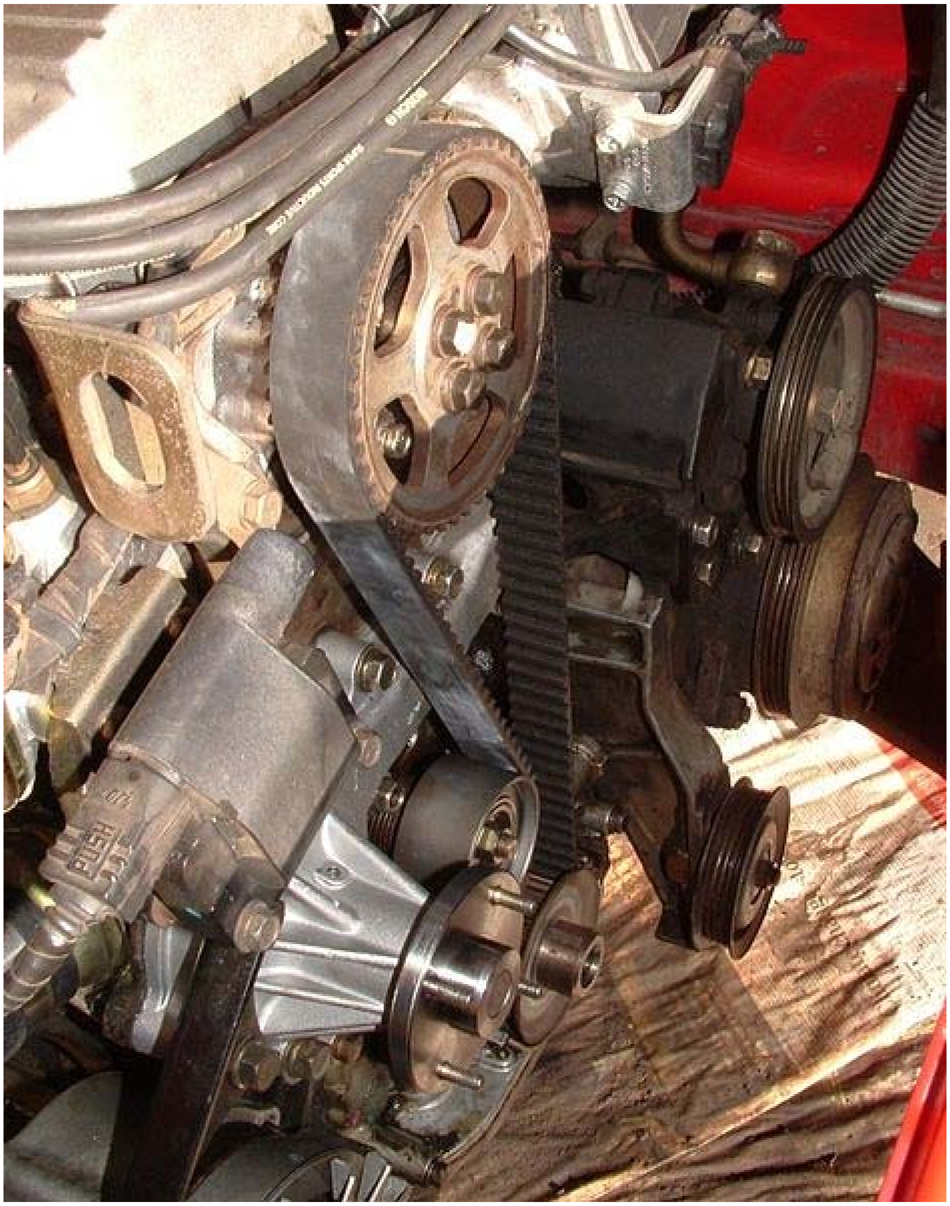
Manufacturers typically cut splines on shafts by milling (with a large runout of the spline as shown on the input shaft in the photograph) or in the mating piece by broaching. Rolling splines onto a shaft is also an option.

To prevent stress concentrations the ends of the splines are chamfered (as opposed to an abrupt vertical end). Such stress concentrations are a primary cause of failure in poorly designed splines.

Chapter 14

Timing Belt

Timing belt



Timing covers, lower pulley, accessory belts removed, exposing timing belt

A **timing belt**, or **cam belt** (informal usage), is a part of an internal combustion engine that controls the timing of the engine's valves. Some engines, such as the flat-4 Volkswagen air cooled engine, and the straight-6 Toyota F engine use timing gears. Timing belts replace the older style timing chains that were common until the 1970s and 1980s (although in the last decade there has been some reemergence of chain use). Some manufacturers, such as BMW, are known for utilizing timing chains, because of their durability. The term "timing belt" is sometimes used for the more general case of any flat belt with integral teeth, although such usage is a misnomer since there is no timing or synchronization involved.

Engine applications

In the internal combustion engine application, the timing belt/chain connects the crankshaft to the camshaft(s), which in turn controls the opening and closing of the engine's valves. A four-stroke engine requires that the valves open and close once every other revolution of the crankshaft. The timing belt/chain does this. It has teeth to turn the camshaft(s) synchronised with the crankshaft, and is specifically designed for a particular engine. In some engine designs, the timing belt may also be used to drive other engine components such as the water pump and oil pump.

Gear or chain systems are also used to connect the crankshaft to the camshaft at the correct timing. However, gears and shafts constrain the relative location of the crankshaft and camshafts. Even where the crankshaft and camshaft(s) are very close together, as in pushrod engines, most engine designers use a short chain drive rather than a direct gear drive. This is because gear drives suffer from frequent torque reversal as the cam profiles "kick back" against the drive from the crank, leading to excessive noise and wear. Fibre gears, with more resilience, are preferred to steel gears where direct drive has to be used. A belt or chain allows much more flexibility in the relative locations of the crankshaft and camshafts.

While chains and gears may be more durable, rubber composite belts are quieter in their operation (in most modern engines the noise difference is negligible), are less expensive and more efficient, by dint of being lighter, when compared with a gear or chain system. Also, timing belts do not require lubrication, which is essential with a timing chain or gears. A timing belt is a specific application of a synchronous belt used to transmit rotational power synchronously.

Timing belts are typically covered by metal or polymer timing belt covers which require removal for inspection or replacement. Engine manufacturers recommend replacement at specific intervals. The manufacturer may also recommend the replacement of other parts, such as the water pump, when the timing belt is replaced because the additional cost to replace the water pump is negligible compared to the cost of accessing the timing belt. In an interference engine, or one whose valves extend into the path of the piston, failure of the timing belt (or timing chain) invariably results in costly and, in some cases, irreparable engine damage, as some valves will be held open when they should not be and thus will be struck by the pistons.

Indicators that the timing chain may need to be replaced include a rattling noise from the front of the engine.

Timing

When an automotive timing belt is replaced, care must be taken to ensure that the valve and piston movements are correctly synchronized. Failure to synchronize correctly can lead to problems with valve timing, and this in turn, in extremes, can cause collision between valves and pistons in interference engines. This is not a problem unique to timing belts since the same issue exists with all other cam/crank timing methods such as gears or chains.

Failure

Timing belts must be replaced at the manufacturer's recommended distance and/or time periods. Failure to replace the belt can result in complete breakdown or catastrophic engine failure. The owner's manual maintenance schedule is the source of timing belt replacement intervals, typically every 60,000 to 90,000 miles (approx 96,000 to 144,000 kilometres). It is common to replace the timing belt tensioner at the same time as the belt is replaced.

The usual failure modes of timing belts are either stripped teeth (which leaves a smooth section of belt where the drive cog will slip) or delamination and unraveling of the fiber cores. Breakage of the belt, because of the nature of the high tensile fibers, is uncommon. Correct belt tension is critical - too loose and the belt will whip, too tight and it will whine and put excess strain on the bearings of the cogs. In either case belt life will be drastically shortened. Aside from the belt itself, also common is a failure of the tensioner, and/or the various gear and idler bearings, causing the belt to derail.

Construction and design

A timing belt is typically rubber with high-tensile fibres (e.g. fiberglass or Twaron/Kevlar) running the length of the belt as tension members.

Rubber degrades with higher temperatures, and with contact with motor oil. Thus the life expectancy of a timing belt is lowered in hot or leaky engines. Newer or more expensive belts are made of temperature resistant materials such as "highly-saturated nitrile" (HSN). The life of the reinforcing cords is also greatly affected by water and antifreeze. This means that special precautions must be taken for off road applications to allow water to drain away or be sealed from contact with the belt.

Older belts have trapezoid shaped teeth leading to high rates of tooth wear. Newer manufacturing techniques allow for curved teeth that are quieter and last longer.

Aftermarket timing belts may be used to alter engine performance. OEM timing belts "will stretch at high rpm, retarding the cam and therefore the ignition. Stronger, aftermarket belts, will not stretch and the timing is preserved. In terms of engine design, "shortening the width of the timing belt reduce[s] weight and friction".

Usage history

The first known timing belt was used in 1945.

The German Glas 1004 was the first mass produced vehicle to use a timing belt in 1962. The first American vehicle to use a timing belt was the 1966 Pontiac Tempest. In 1966, Vauxhall started production of the Slant Four overhead cam four-cylinder design which used a timing belt, a configuration that is now used in the vast majority of cars built today.