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# Mechanical Power Transmission Fundamentals

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## Gear Trains

Gear trains are multiple sets of gears meshing together to deliver power and motion more effectively than can be accomplished by one set of gears. Figure 1 shows the various types of gears that can be used in a gear train. Gears 2 and 3 can be either spur or helical gears and are mounted on parallel shafts. Gears 4 and 5 are bevel gears that mount on shafts that are 90° apart. Gears 6 and 7 comprise a worm gear set and mount on shafts that are at 90° but are non-intersecting. Worm gears have a high ratio and can be non-reversing.

Figure 2 depicts a simple gear train at the top and a compound gear train at the bottom. The simple gear train consists of four in-line gears in mesh. The compound gear train consists of the same four gears, except two are located on the same shaft. The overall ratio of the simple gear train is the product of the three individual ratios and is as follows:

$$n_2/n_5 = (N_3/N_2)(N_4/N_3)(N_5/N_4)$$

$n$  equals the rpm and  $N$  equals the number of teeth in the respective gears. When cancelling out like quantities, the equation can be reduced to the following:

$$n_2/n_5 = (N_5/N_2)$$

Suppose Gear 5 has 64 teeth and Gear 2 has 16 teeth, then the overall gear train ratio would be 4 to 1. If Gear 2 is considered the driving member, the simple gear train in Figure 2 is a speed reducing gear train. If the rpm of Gear 2 is 400, the rpm of Gear 5 is 100. Gears 3 and 4 are called idler gears since they have no effect on the overall gear train ratio.

The equation for the overall ratio of the compound gear train is the product of the two individual ratios and is as follows:

$$n_2/n_5 = (N_4/N_2)(N_5/N_3)$$

Assuming that the same four gears are used and that Gear 3 has 32 teeth and Gear 4 has 48 teeth, the overall ratio for the compound gear train is:

$$n_2/n_5 = (48/16)(64/32) = 6$$

The following can be said about using compound gear trains over simple gear trains:

- 1) More ratios can be obtained.
- 2) The design is more compact.
- 3) There is one less shaft.

Figure 1

Various Gear Types in a Train

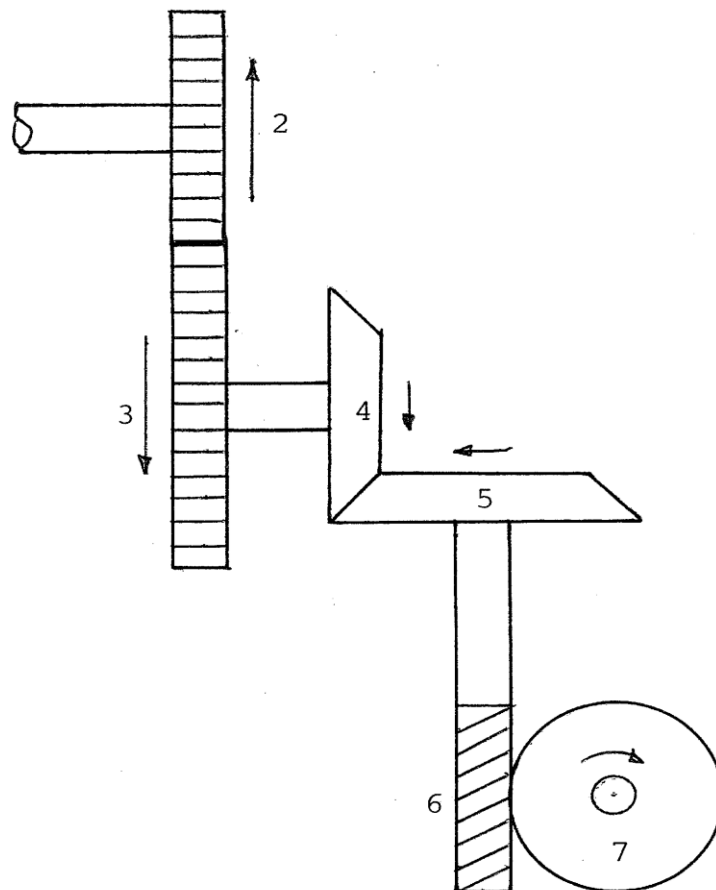
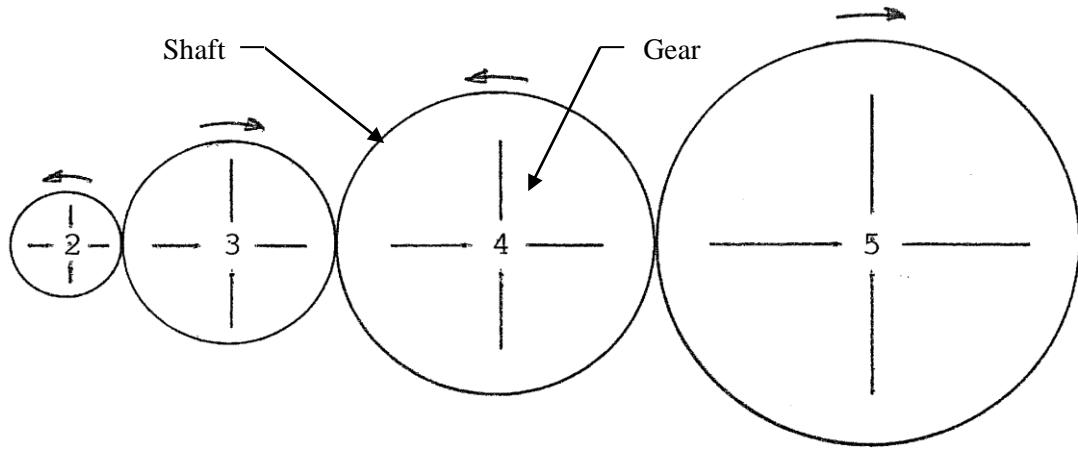
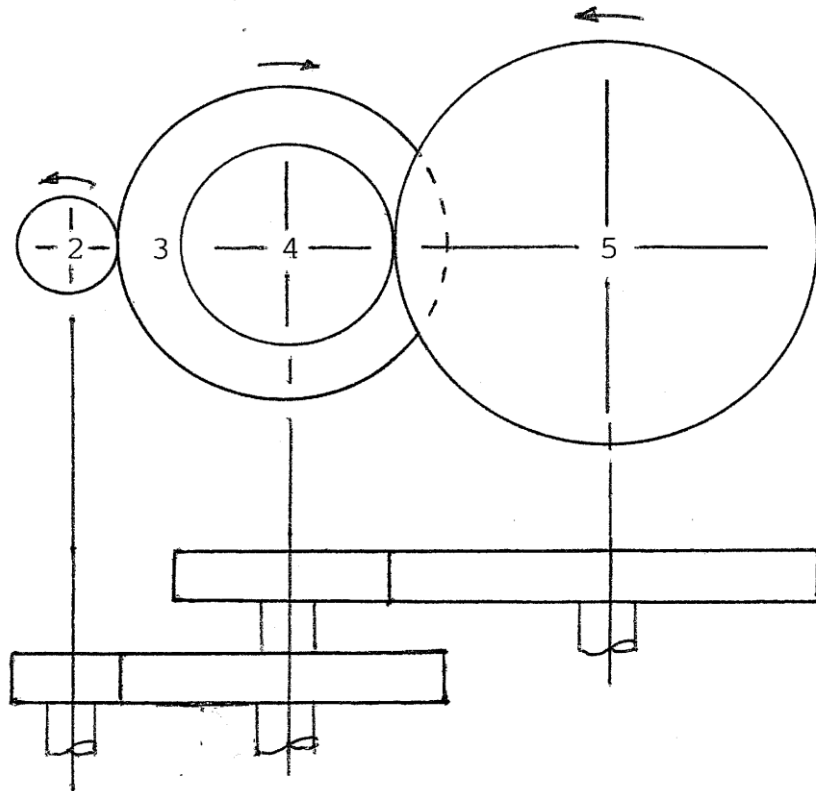


Figure 2



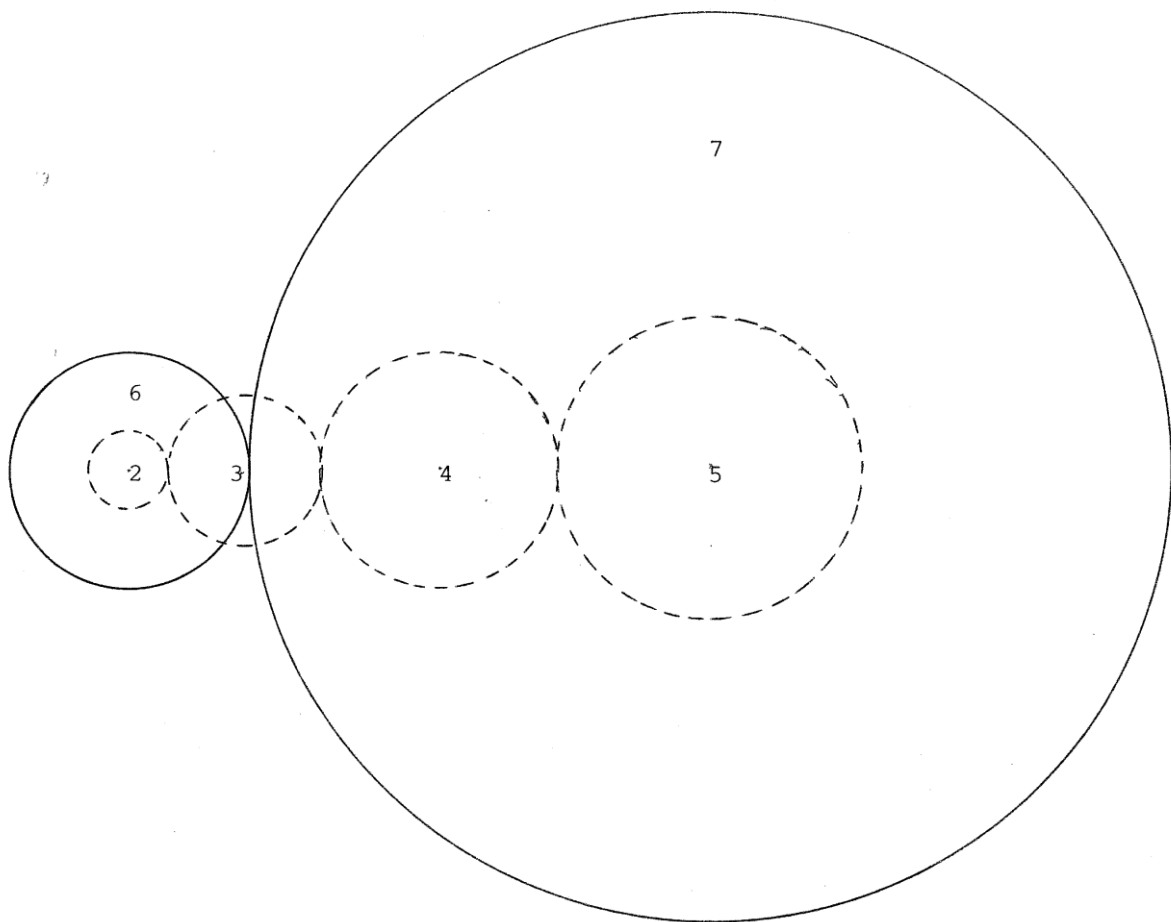
Simple Gear Train



Compound Gear Train

Figure 3 shows that very large Gears 6 and 7 are needed if a simple gear train is not used. The effect is even greater for a compound gear train.

Figure 3



Gears 6 and 7 needed if gear train is not used.

## Planetary Gears

Planetary gears consist of a set of gears as shown in Figure 4. The sun gear is surrounded by one or more planet gears which ride inside a ring gear. The planet gears are supported by a carrier. Planetary gears are useful in that they can deliver power over more than one path in a high ratio inline gear setting. One way to do this is to drive the sun gear, hold the ring gear from rotating, and take off from the carrier on the opposite side of the set. The following equation is commonly used to calculate the speed relationships with planetary gear sets:

$$n_c(1 + N_s/N_r) - n_s(N_s/N_r) = n_r$$

$n_c$  is the carrier rpm.

$N_s$  is the number of teeth in the sun gear.

$N_r$  is the number of teeth in the ring gear.

$n_s$  is the sun rpm.

$n_r$  is the ring gear rpm.

Let us assume that in Figure 4 the number of teeth in the sun gear equals 48, the number of teeth in the stationary ring gear is 112, and the input speed to the sun gear is 100 rpm. Using the above formula, we can now calculate the output rpm of the carrier as follows:

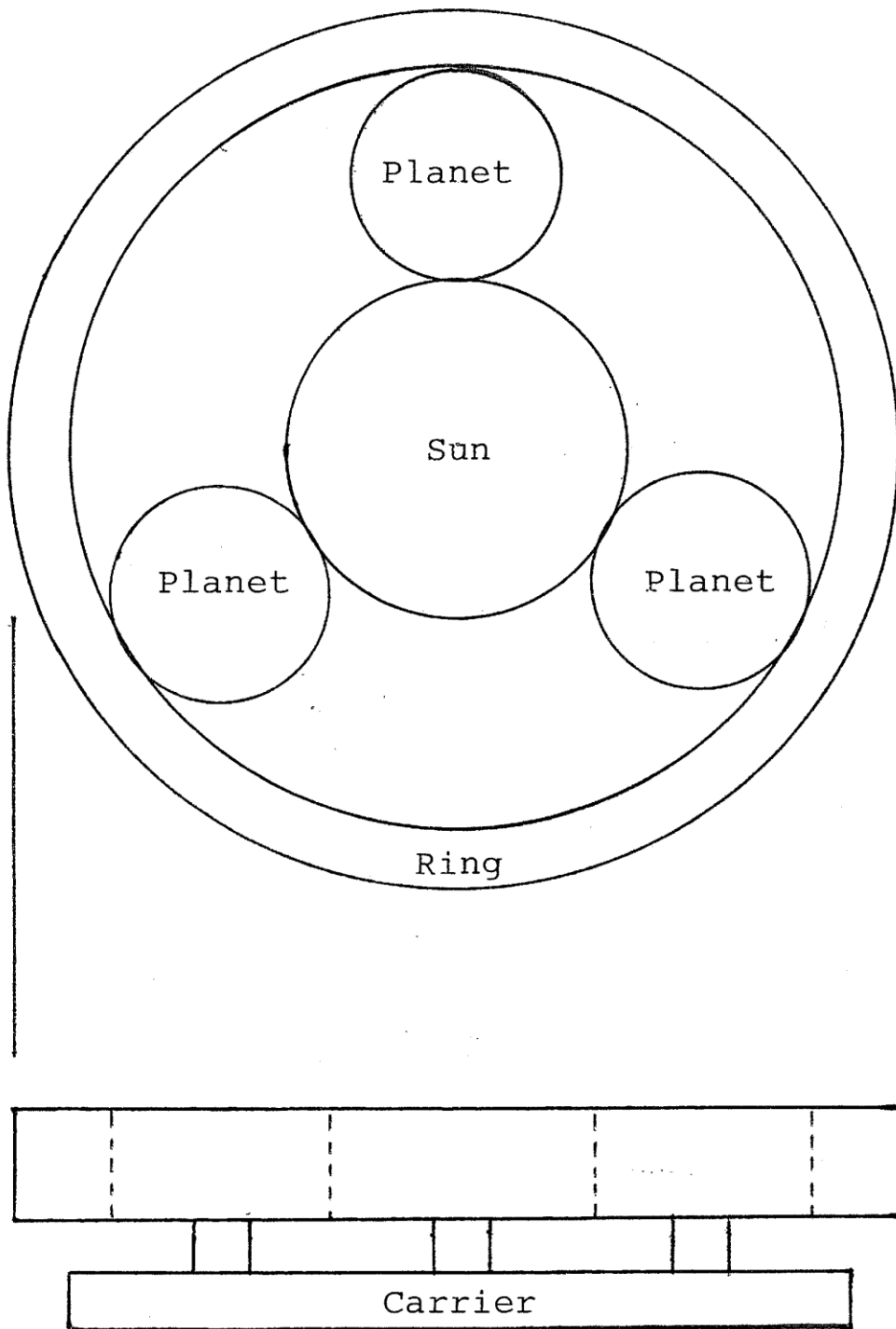
$$n_c(1 + 48/112) - 100(48/112) = 0$$

$$n_c = 30$$

The planetary gear set of Figure 4 can deliver over a 3/1 speed reduction when driving the sun and taking off from the carrier. It can be shown using this relationship, that there are other possibilities planetary gears have in delivering various speed ratios. Planetary gears are used in wind turbine gear boxes. These gearboxes speed up the low rpm rotor rotation to a higher speed generator rotation.



Figure 4



Planetary Gear Set

## Differential Gears

Figure 5 shows the arrangement of the gears in the center section of an automotive drive axle. Power is transmitted from the pinion gear to the ring gear. From there it travels through the differential gears to the two output shafts. As long as the vehicle is traveling in a straight line, the four differential gears rotate as a unit and do not rotate with respect to each other. When a vehicle travels around a corner, the differential gears rotate at different speeds allowing the outer wheel to travel further than the inner wheel so the tires do not skid on the pavement surface. A disadvantage of the differential gear system is that when one wheel is on a slippery surface, all the power is sent to that wheel making it slip rendering the vehicle immobile. Some vehicles have slip clutch plates mounted behind the differential gears which allows the vehicle to propel itself using the one wheel that is still on a tractive surface. Figure 6 shows the cross section of a complete automotive drive axle.

The following relationship holds true for the differential gears:

$$n_r = \frac{(n_{l_o} + n_{r_o})}{2}$$

$n_r$  is the rpm of the ring gear.

$N_{l_o}$  is the rpm of the left output shaft.

$N_{r_o}$  is the rpm of the right output shaft.

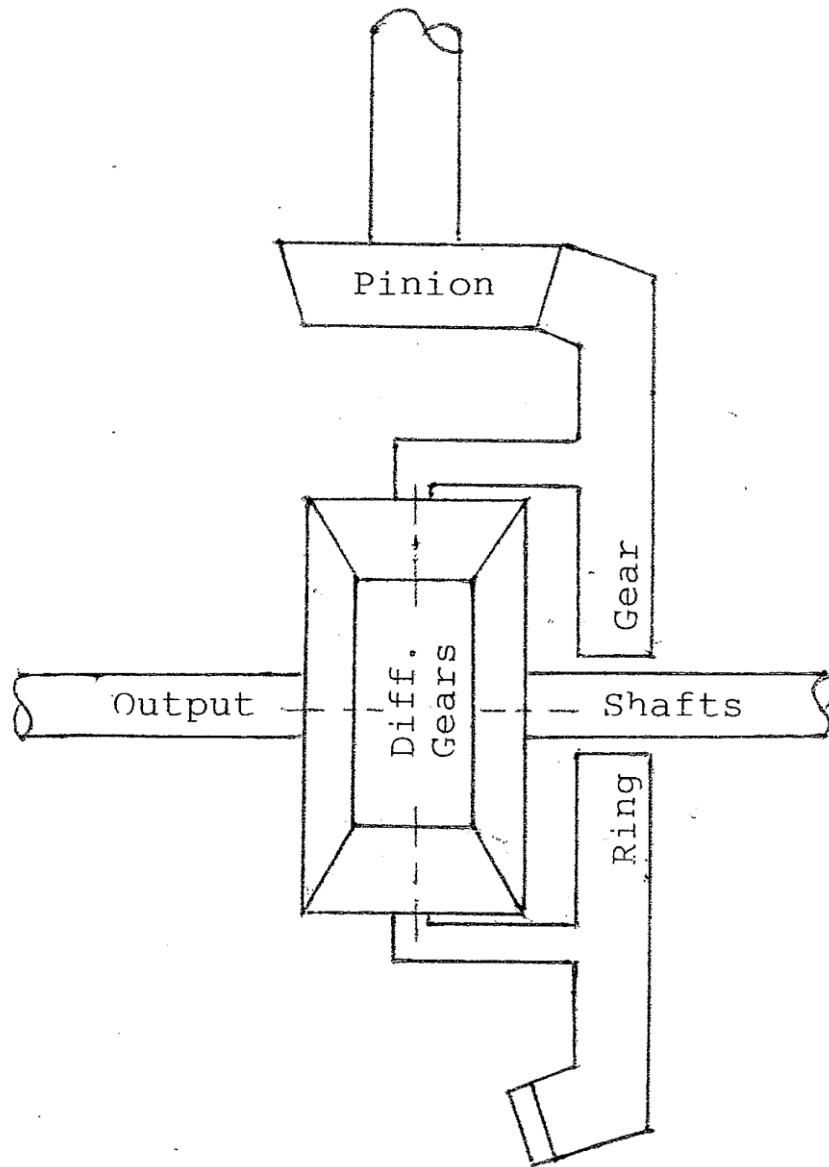
Let us assume that the pinion gear has 30 teeth and that the ring gear has 90 teeth. With the left hand wheel of the vehicle raised up and free to rotate and the right hand wheel resting firmly on the pavement, what is the rpm of the left hand wheel when the pinion gear rotates at 1200 rpm? The rpm of the ring gear is as follows:

$$1200 \times 30/90 = 400\text{rpm}$$

Using the above relationship, the rpm of the left hand wheel which is free to rotate is as follows:

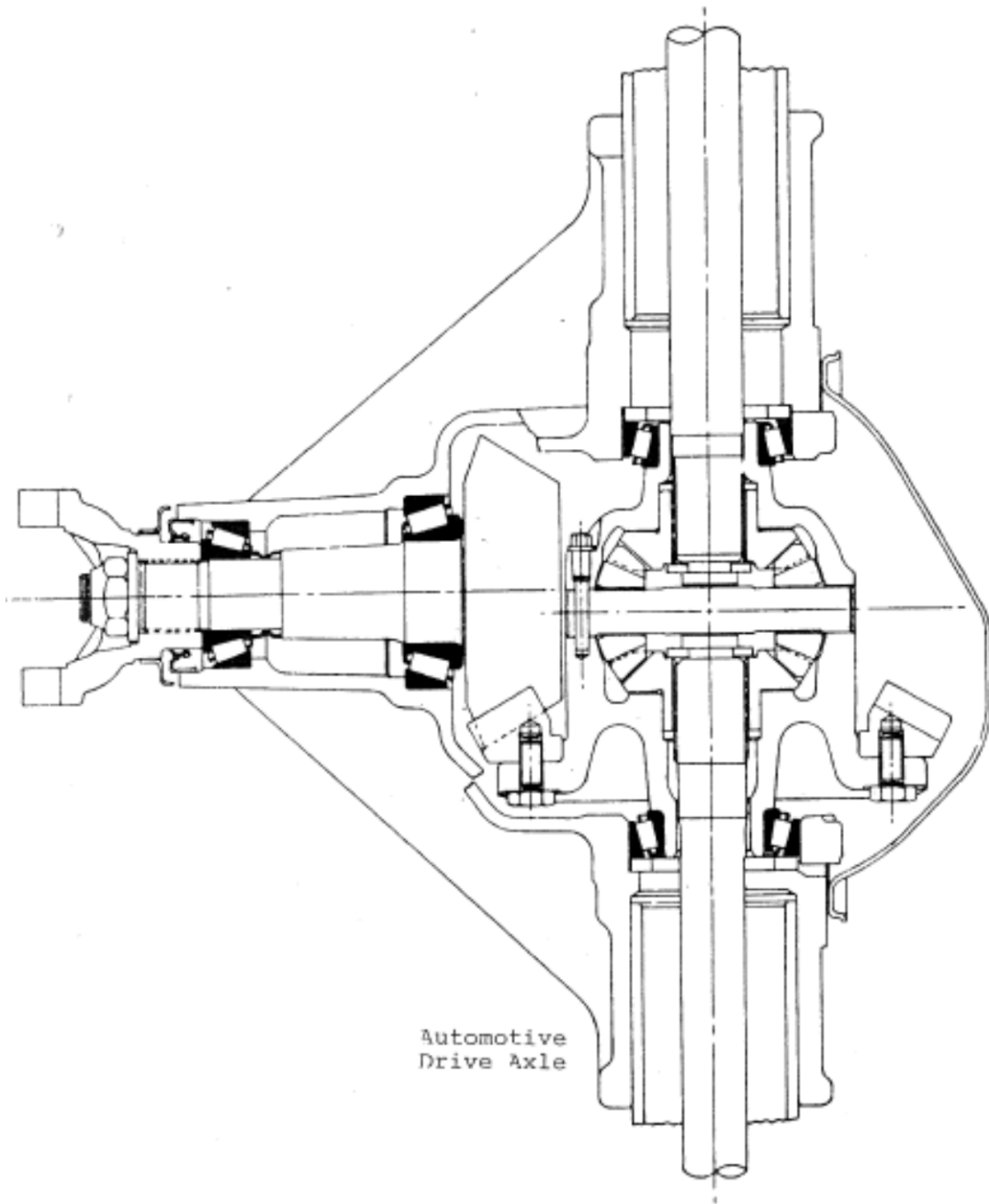
$$400 = (n_{l_o} + 0)/2 = 800\text{rpm}$$

Figure 5



Differential Gear Arrangement

Figure 6



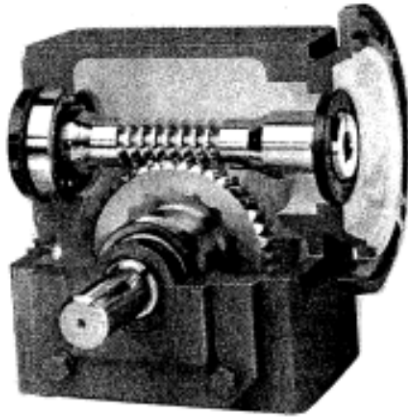
## Gearboxes

Gearboxes contain one or more pair of gears inside a housing which has an input shaft and one or more output shafts. The output shafts may be located on the sides or at the back of the gearbox. Gearboxes contain a gear lubricant, are sealed, and usually operate maintenance free. Connected to the input shaft is a high speed power source such as a motor and connected to the output shafts are devices which generally use lower rpms and higher torques to perform a particular task. The device may include a machine tool, a conveyor, an elevator, or the wheels of an automobile.

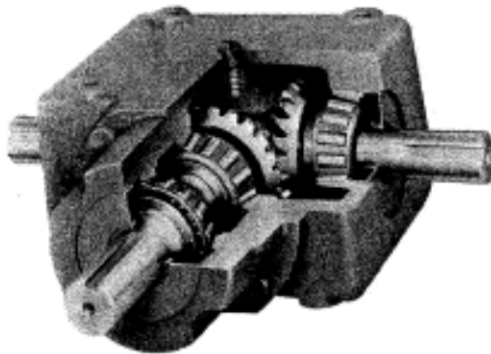
Figure 7 has a worm gearbox at the top and a bevel gearbox at the bottom. Worm gearboxes are generally high reduction devices with ratios ranging from 5/1 to 60/1 for single reduction units such as shown in Figure 7 to 3600/1 for double reduction units. Because of the high amount of sliding that occurs at the mesh, worm gears operate at efficiencies below that of other types of gears. To minimize this effect, the gear is usually made of a material with a low coefficient of friction such as bronze. Worm gears can be made to be non-reversing by keeping the lead angle of the worm thread low.

Figure 7 has a bevel gearbox at the bottom. Bevel gearboxes have input and output axes 90° apart like worm gearboxes; however, bevel gearbox axes intersect as opposed to worm gearbox axes being offset. Bevel gearboxes generally have lower ratios than worm gearboxes and can be used as speed increasers as well as speed reducers. Bevel gearboxes having all steel gears can deliver more horsepower than worm gearboxes with bronze gears. Spiral bevel gears are stronger and quieter than straight bevel gears but are less efficient.

Figure 7



Worm Gearbox

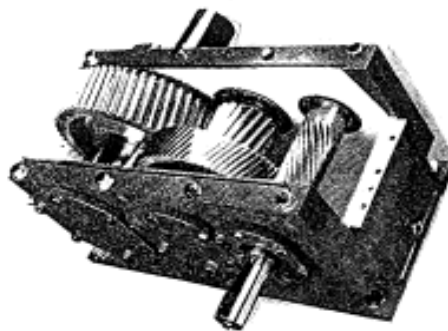


Bevel Gearbox

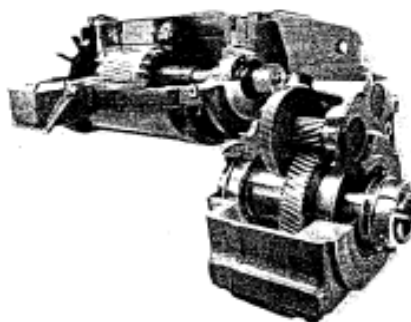
Images courtesy of Emerson Power Transmission.

Figure 8 has a double reduction gearbox on top and a gearbox-motor combination unit on bottom. The double reduction gearbox can give twice the ratio as a single reduction gearbox in a slightly larger package. It features helical gears for quieter, more powerful operation over spur gears. The motor-gearbox unit is an integral package that features a double reduction helical gearbox directly attached to a drive motor. Integral motor mounting features excellent alignment with the gearbox input shaft for smooth, vibration-free operation.

Figure 8



Double Reduction Gearbox



Gearbox With Motor

Images courtesy of Emerson Power Transmission.

## Multi-Speed Gearboxes

The manual transmission of an automobile is a multi-speed gear box. It incorporates varying the means of reduction through the gearbox in steps for controlling vehicle acceleration and deceleration. Figure 9 has a schematic of a three-speed automatic synchromesh manual transmission. It is shown in the neutral or non-drive position. There are three shafts and three sets of gears. The shafts include the input shaft (1), the counter shaft (2), and the output shaft (3). The gears include the counter shaft drive gears (4) which are always engaged, the first gearset (5) where the upper gear is shown slid out of mesh, and the second gearset (6) in which the upper gear spins freely on the shaft. The synchromesh clutch (7) is used for second and third gear and is shown in the central or neutral position.

Figure 10 shows the four shift positions of the manual transmission shown in Figure 9. The top schematic in Figure 10 has the transmission in the neutral position which is what is seen in Figure 9. In the neutral position, the input shaft (1) drives the counter shaft (2) which spins freely. The second schematic shows the transmission in first gear. Through a manually operated lever system, the upper first gear (5) is slid into mesh with the lower first gear allowing power to be delivered to the output shaft (3). The next schematic has the transmission in second gear. The upper first gear (5) is slid out of mesh and the synchronizer clutch (7) positively connects the upper second gear (6) to the output shaft (3) allowing power to be transmitted through the transmission.

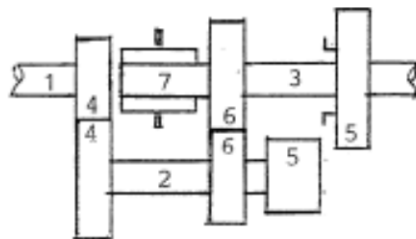
Figure 11 shows the operation of the synchronizer with the second gear. The upper figure shows the synchronizer rotating with the output shaft next to the upper second gear which is free to spin on the same output shaft. The next figure shows the synchronizer moved to the right until the conical surfaces of the synchronizer and the gear touch. This action causes the second gear and the output shaft to rotate as a unit. The third figure has the synchronizer moved all the way to the right until the teeth of the two members mesh. This mesh proves to be a smooth engagement since the two are rotating at essentially the same speed.



Figure 9

Automotive Manual Transmission Schematic

(Shown in Neutral Position)



No 1 is the input shaft (driven by engine).

No 2 is the counter shaft.

No 3 is the output shaft (powers vehicle).

No 4 are counter shaft drive gears (always engaged).

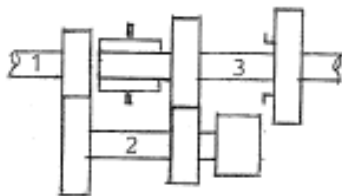
No 5 are first gears (upper slides on shaft).

No 6 are second gears (upper spins freely).

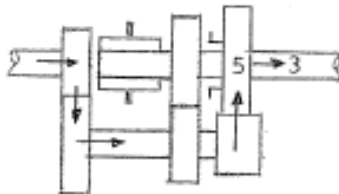
No 7 is the synchronizing clutch (neutral position).

Figure 10

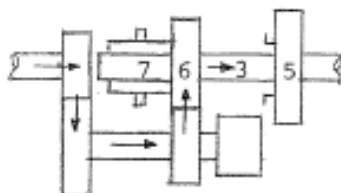
Automotive Manual Transmission Shift Positions



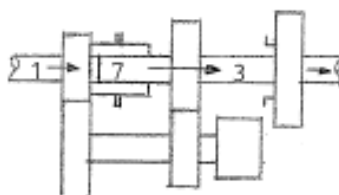
Neutral:  
Input shaft(1) drives counter shaft(2)  
which spins freely. No power delivered  
to output shaft(3).



First:  
Upper first gear(5) slid to the left  
engaging the output shaft(3).



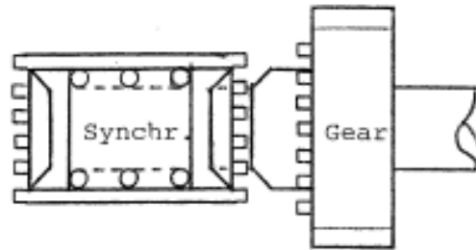
Second:  
Upper first gear(5) is disengaged.  
The synchronizing clutch(7) locks  
second gear(6) to the output shaft(3).



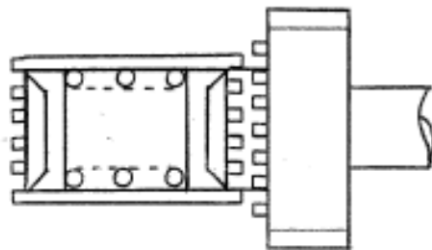
Third:  
The synchronizing clutch(7) connects  
the input shaft(1) to the output  
shaft(3) resulting in direct drive.

Figure 11

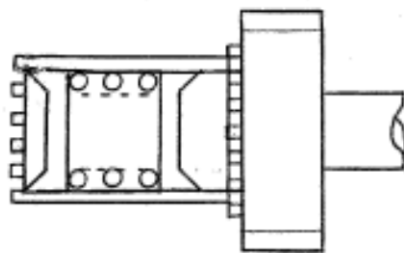
Manual Transmission Synchronizer



Synchronizer rotates with shaft.  
Gear free to spin on same shaft.



Synchronizer moved to the right.  
Conical surfaces contact rotating  
synchronizer and gear as a unit.



Synchronizer moved further to the  
right until teeth positively engage.

The last schematic of Figure 10 shows the synchronizing clutch (7) positively connecting the input shaft (1) directly to the output shaft (3) resulting in direct drive through the transmission. The synchronizing clutch is moved to the left creating the same action that is described above.

Nominally the ratios for gears are 2.75 for first, 1.65 for second, 1.0 or direct drive for third, and 3.25 for reverse which incorporates another shaft not shown in the figures. There are manual transmissions with more than three speeds which incorporate additional gears and synchronizing clutches.

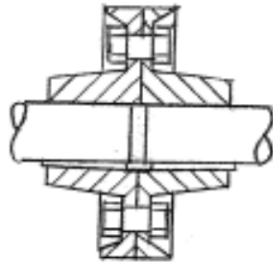
## Couplings

A coupling is a device that connects two shaft ends together so that power may be transmitted through the juncture. There is a rigid coupling, a flexible coupling, and a fluid coupling. The simplest type is a flanged coupling which is classified as a rigid type. Since it is rigid, it is used on shafts that are in good alignment. The drawing at the top of Figure 12 is of a flanged coupling. It consists of two members which are loosely fitted on the shafts. When the two members are bolted together, tapered keys are wedged between the shaft and the coupling locking the two shafts together. Flanged couplings can be assembled to the shafts with loose fitting keys if the flanges are a press fit on the shaft. Flanged couplings are used in wind turbine drive trains.

As previously mentioned, the flanged coupling is a rigid type that is used to connect shafts that are closely aligned. For shafts that are not closely aligned, a flexible coupling is used. One such device is called a double slider coupling. The middle drawing of Figure 12 is of a double slider coupling. It can be seen that it has a center piece with raised tongues  $90^\circ$  apart that fit in grooves in each end piece. The end pieces are set screwed to the shafts while the center piece is free to move to compensate for shafts that have offset and misalignment. Other flexible couplings use center pieces with rubber, splines, or chains.

For shafts with higher amounts of misalignment, a coupling called a universal joint is used. Universal joints can be used on shafts with as much as  $30^\circ$  of misalignment. At the bottom of Figure 12 is a universal joint. It can be seen that it has two opposing yokes that are connected to a cross-shaped center piece. Needle bearing (very small diameter roller bearings) are used at the four connection points to reduce friction. Universal joints that operate under misalignment do not produce a constant angular velocity output. The output velocity fluctuates with each revolution causing unwanted vibrations. This effect increases with increasing amounts of misalignment. For this reason, universal joints are frequently used in pairs which results in a constant velocity output.

Figure 12



Flanged Coupling



Double Slider Coupling

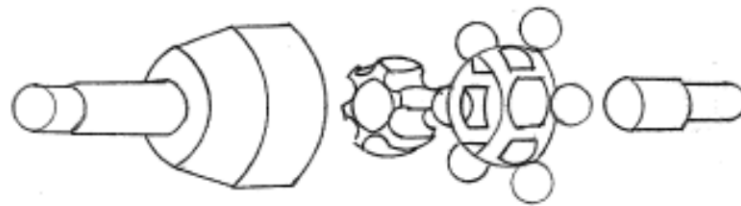


Universal Joint

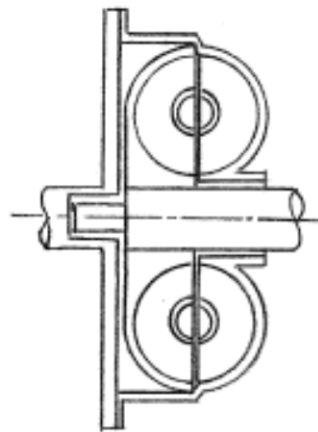
A Rzeppa universal joint can also operate under a high degree of misalignment. Rzeppa joints are used in front drive shafts of front engine, front drive automotive vehicles. The drawing at the top of Figure 13 shows the component parts of a Rzeppa joint. There is a row of six balls in a cage that rides on the outside diameter of the inner race and the inside diameter of the outer race (housing). The ball row operates at an angle halfway between the inner and outer races making the Rzeppa joint act like a bevel gear with balls rather than

teeth doing the driving. Because of this operating characteristic, the output velocity of a Rzeppa joint is constant.

Figure 13



Rzeppa Universal Joint



Fluid Coupling

The third kind of coupling to go along with rigid and flexible couplings is the fluid coupling. An important use of fluid couplings is in automotive vehicles where it is mounted between the engine and transmission. The drawing of such a unit is at the bottom of Figure 13. It can be seen that the main body is in the shape of a torus (donut). On the left is the input shaft to which the flywheel is attached. The flywheel is connected to the right side of the torus which contains a circular row of blades called the impeller. The impeller, when rotated, and with the aid of centrifugal force, delivers oil across the narrow gap to the left side of the torus where another row of blades called the runner is located. The force of the oil rotates the runner which is attached to the output shaft sending power to the vehicle drive wheels. The oil is then recirculated inward and back to the impeller to repeat the cycle.

In the fluid coupling, power is not transmitted by mechanical means alone. At one point in the cycle, all the power is transmitted by the oil across the narrow gap between the two rotors. This feature makes fluid couplings an excellent isolator of engine shock and vibration. Also, fluid couplings negate the need for a manually operated clutch in a vehicle.

Since their inception, there have been a number of improvements made to automotive fluid couplings which has increased their performance. Curved blades on the impeller and runner have increased the amount of torque transmitted between the two. The addition of a stationary row of blades called the reactor between the inner part of the impeller and the runner reduces the drag on the impeller. Mounting the reactor on a one-way clutch eliminates a problem when, during certain operational conditions, oil from the impeller impinges on the back side of the reactor blades. With the addition of a number of new features, automotive fluid couplings have now become to be called torque converters.



## Clutches

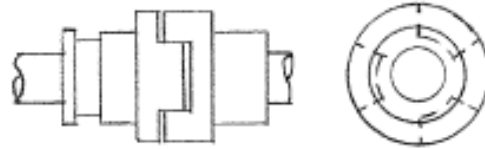
Clutches are couplings that are used to engage and disengage the power that is transmitted between two connecting shafts. Positive drive clutches are designed to deliver full power without slippage. Friction clutches are designed to slip at some predetermined torque setting. This allows smooth engagement and disengagement and also protect against overload.

The three jaw clutches shown at the top of Figure 14 is a positive drive unit designed to deliver full power in either direction of rotation without slippage. It is shown in the fully engaged position. The left hand member is splined to the shaft while the right hand member is fixed to its shaft. For engagement or disengagement, the left hand member is moved laterally by means of a mechanical linkage that fits into the circular groove on its hub. Engagement speed for a three jaw clutch is limited to approximately 10 rpm. Disengagement speed is not limited for clutches with precision machined mating surfaces.

Shown in the middle of Figure 14 is a spiral jaw clutch. Spiral jaw clutches are also positive drive units but are designed to deliver power in one direction of rotation only. For rotation in the opposite direction, units are made with the spiral reversed. Engagement and disengagement is similar to the square jaw clutch. Maximum engagement speed is approximately 150 rpm. Disengagement speed is not limited for clutches with precision machined surfaces.

A basic drawing designed to show the fundamental principles of friction clutches is shown at the bottom of Figure 14. It can be seen that there is a friction disc sandwiched between two rotating flanges. The left hand member is splined to the shaft while the right hand member is fixed to its shaft. A helical spring acts on the left hand member supplying the force needed to deliver the required torque. A mechanical linkage that fits into the rotary groove on the hub of the left hand member is used to provide the lateral movement necessary to engage and disengage the clutch. Engagement and disengagement speeds are not limited with friction clutches as they are with positive drive clutches.

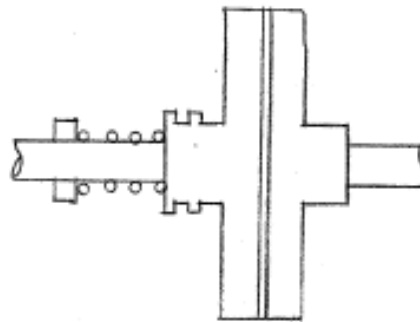
Figure 14



Three Jaw Clutch



Right Hand Rotation      Left Hand Rotation  
Spiral Jaw Clutch



Friction Clutch

Friction discs make these functions perform smoothly and they also act as safety devices by preventing system overload. Good disc materials are bronze and cast iron. Friction clutches can have more than one disc to increase torque carrying capacity.

There are a number of clutches used in automotive vehicles. A friction clutch based on the one on Figure 14 is used in manual transmissions. Automatic transmissions used hydraulically operated clutches to change gears. Automatic transmissions and torque converters have one-way clutches. One-way clutches, as the name suggests, allow rotation in one direction only. A roller or a sprag (flattened roller) ride up a ramp and lock into place preventing rotation in one direction while allowing it in the other direction. There is an electronically operated friction clutch that controls the air conditioning compressor. There is a friction clutch that controls the engine cooling fan in some automotive vehicles. A viscous fluid thickens as it heats up increasing the speed of the fan and cooling the engine. Clutches play a very important role in automotive vehicle power systems.

## Belts and Pulleys

Belts and pulleys are used when the distance between shafts is too great to make it practical to use gears. There are basically two kinds of belts: flat belts and V belts. Flat belts, as the name suggests, are wider and thinner than V belts which have a V shaped section. Both kinds are made of fabric which is impregnated with rubber. Belts are a quiet and efficient means of transmitting power and are able to absorb vibration. A cross section of a flat belt and pulley is shown at the top of Figure 15 while a section of a V belt and pulley is shown at the bottom. Flat belt pulleys have a crown shaped outer surface which acts to keep the belt centered. V belt pulleys have an internal angle slightly less than the belt. This produces a wedging action of the belt into the pulley aiding traction. Generally speaking, flat belts are as efficient and can run as fast as gears, but deliver only a fraction of the power. V belts are as efficient but can run only about 60% of the speed of gears and deliver a fraction of the power.

V belts are used extensively in the front end of automobile engines to power the various vehicle accessories. At the top of Figure 16 is a diagram of a typical vehicle engine accessory drive system. It can be seen that the engine crankshaft drive pulley has one belt that drives the fan pulley and the power steering pulley and a second that drives the fan pulley and the alternator pulley. The fan pulley has a third belt that drives the air conditioner pulley.

At the bottom of Figure 16 is a diagram of a typical engine accessory drive system using a single poly V belt. At the top of Figure 17 is a cross sectional view of a typical poly V belt. It can be seen that it is wider and thinner than a standard V belt and, as the name suggests, has a number of smaller V shaped gripping surfaces instead of the one larger surface characteristic of standard V belts. Poly V belts have a distinct advantage over standard V belts and are replacing standard V belts in automotive engine accessory drive systems. They are stronger, more flexible, use smaller diameter pulleys, and last longer than standard V belts. The back of poly V belts acts like a flat belt and can be used to drive pulleys. Because of these advantages, the design package using poly V belts is smaller and simpler than that using standard V belts.

Figure 15

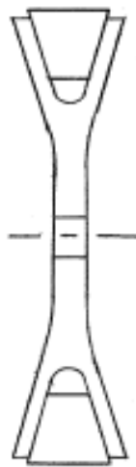
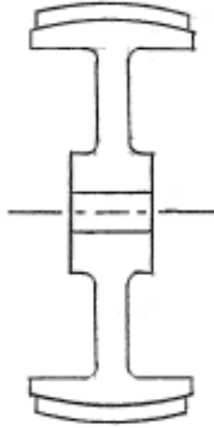
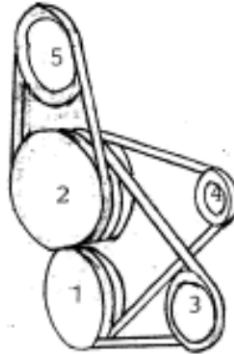
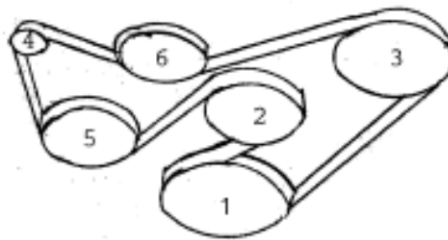


Figure 16



Three V Belt System

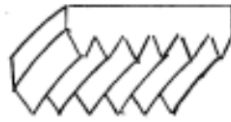
- #1 is the crankshaft drive pulley.
- #2 is the fan pulley.
- #3 is the power steering pulley.
- #4 is the alternator pulley.
- #5 is the air conditioner pulley.



Single Poly V Belt System

- #1 is the crankshaft drive pulley.
- #2 is the fan pulley.
- #3 is the power steering pulley.
- #4 is the alternator pulley.
- #5 is the air conditioner pulley.
- #6 is the belt tensioner pulley.

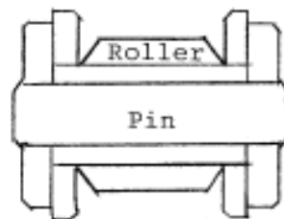
Figure 17



Poly V Belt



Cog Belt



Roller Chain Link Assembly

It is common practice to use a belt tensioner with poly V belts but the advantages far outweigh any disadvantage this may have.

At the middle of Figure 17 is a view of a cog belt. A cog belt, as can be seen, has the small V shaped ribs running across the belt rather than around the belt as the poly V belt. Advantages of cog belts are greater flexibility and smaller pulleys than other belts. They are used when exact speed ratios between pulleys are required such as in automotive valve timing systems.



## Chains and Sprockets

Chains are used for lower speed applications when the shafts are too far apart for gears and the torques are too high for belts. They are also used when exact speed ratios are needed. At the bottom of Figure 17 is a cross sectional view of a typical roller chain link assembly. The roller rotates on a bushing which fits on a pin. The roller link assemblies are held together by link plates on each side. The high efficiency and long life of roller chains is dependent on periodic lubrication of the link assemblies. Chains are used on engines, machines, conveyors, and heavy duty apparatus such as oil field and mining equipment. The sprockets for chains have teeth similar to gears. Sprockets with an odd number of teeth wear better than those with an even number of teeth. The recommended number of teeth for smaller sprockets running moderate speeds is from 15 to 23. Sprockets running at low speeds can have as few as 7 teeth.