Part 5 of 6:
SHAFTS AND BEARINGS

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1 Shafts

Previous projects have pointed out the importance of machine elements such as fasteners, springs, gears, valves, pipe fittings, etc., in engineering design. **SHAFTS**, too, are a basic, important and very common machine element. We have already come across some examples of shafts in earlier projects, e.g. gears must be mounted on some sort of shaft, and a gate valve or globe valve is opened and closed by a hand-wheel turning another type of shaft often referred to as a **SPINDLE**.

It is normal practice to buy items such as gate or globe valves, gears, pulleys and many other items as standard components, "off the shelf". In other words, a manufacturer makes large quantities of industry-standard items which are sold in many different locations for many different purposes. **Shafts generally do not fall into this category**. A shaft is usually designed to perform a specific task in a specific machine. There may of course be thousands of similar machines produced, each using a shaft of that design, and the manufacturer may provide extra shafts as "spare parts", but that shaft design generally has no use outside the machine for which it was designed. It follows that designers will frequently be called upon to design shafts and it is therefore important for them to understand the requirements of shafts and the design features needed to fulfil these requirements.

1.1 Definitions

Since shafts take on several different configurations and are used for many different purposes, several different definitions are in common use, as listed below. The nomenclature is not always clear cut and there is often an overlap of function and therefore of definition.

Shaft — In general, a **ROTATING** member used for the transmission of power.

Axle — Generally a **STATIONARY** member used as a support for rotating members such as bearings, wheels, idler gears, etc.

Spindle — A short shaft, usually of small diameter, usually rotating, e.g. valve spindle for gate valve, but consider also the **HEADSTOCK SPINDLE** of a lathe, which is quite large and usually has a hole right through its centre (see Figs 5-8, 5-9 below).

Stub shaft — A shaft which is integral with an engine, motor or prime mover and is of suitable size, shape and projection to allow its easy connection to other shafts.

Line shaft (or power transmission shaft) A shaft connected to a prime mover which transmits power to a number of machines – now mostly superseded by machines having individual motors.

Jack shaft A short shaft used to connect a prime mover to a machine or another shaft. May also be a short shaft placed as an intermediate shaft between a prime mover and driven machine.

Flexible shaft Permits the transmission of power between two shafts (e.g. motor shaft and machine shaft) whose rotational axes are at an angle or where the angle between the shafts may change.

Some examples of different types of shafts follow.

1.1.1 Shafts

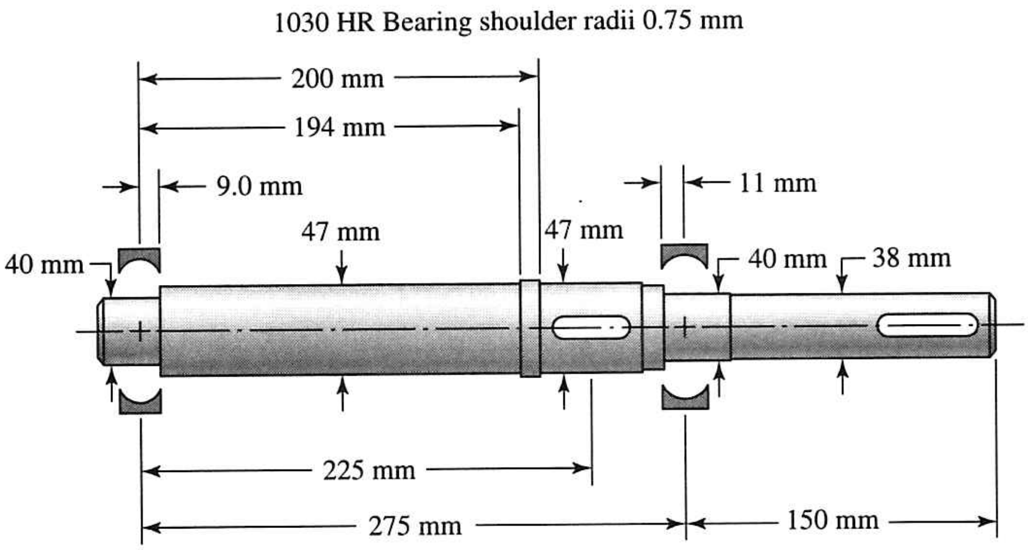
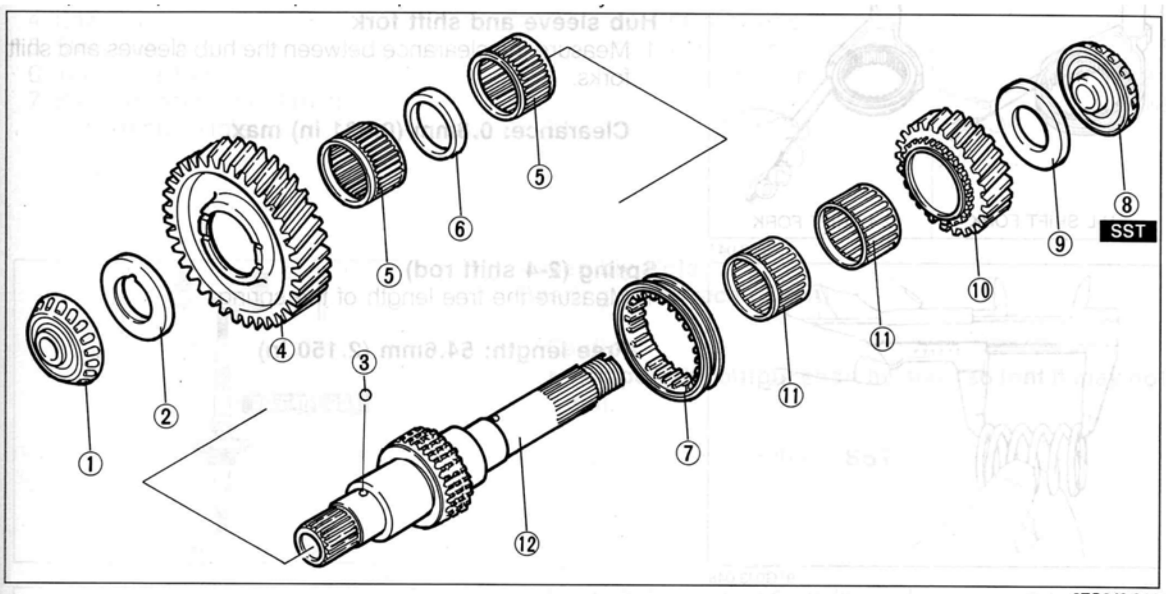


Figure 5-1 A preliminary drawing of a **SHAFT** drawn for design purposes. The locations of two support **BEARINGS** are shown schematically. There are two **KEYWAYS**, suggesting something like a pulley on the right-hand end and perhaps a gear between the two bearings, with **SHOULDERS** for axial location of the gear and the two bearings. Note that dimensioning, although clear and complete, is **NOT** to Australian Standard.
Shigley, J E, Mischke, C R, Mechanical Engineering Design, 6E, 2001, McGraw Hill, page 1141.



1. Bearing inner race (Front)
   Disassembly Note..................... page J3–19
   Inspect for damage and rough rotation
2. Thrust washer
3. Steel ball
4. Low gear
   Inspect for damage and wear
5. Needle bearing
   Inspect for damage and rough rotation
6. Spacer
7. H-L hub sleeve
8. Bearing inner race (Rear)
   Disassembly Note..................... page J3–19
   Inspect for damage and rough rotation
9. Thrust washer
10. High gear
    Inspect for damage and wear
11. Needle bearing
    Inspect for damage and rough rotation
12. Output shaft

Figure 5-2 An “exploded view” of an assembly from the high-low speed transfer case of a Mazda 4WD vehicle. Item 12 is described as the **OUTPUT SHAFT**. It features steps and shoulders, splines, a thread, and an integral “gear” which is part of the change mechanism for high-low speed. All the components shown fit onto the assembled shaft.
From Mazda T2600 Workshop Manual, 1989, page J3-19

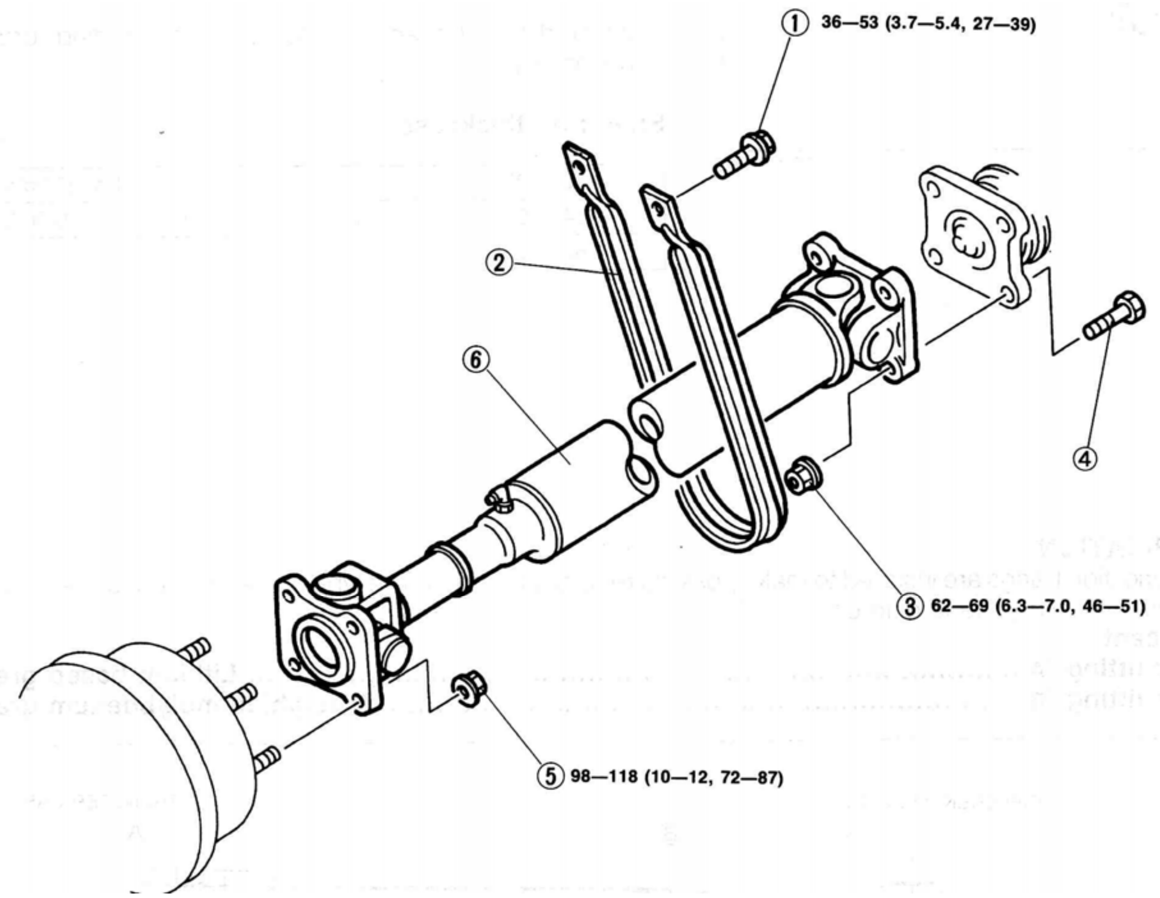


Figure 5-3 A shaft known variously as a **DRIVESHAFT**, **TAILSHAFT** or **CARDAN SHAFT** (and sometimes as a **JACK SHAFT**) used to transmit power and torque from the rear of an automotive gearbox (on the left) to the input shaft of the differential, which is known as the **PINION SHAFT** (on the right). The driveshaft is fitted with **UNIVERSAL JOINTS** at each end, allowing the rear axle to move up and down and still transmit the drive. The shaft also features a **SLIP-JOINT** (near the left-hand end) to allow for changes in shaft length as the rear axle moves up and down. The U-shaped component is a "catcher" to prevent the driveshaft from falling to the roadway should either universal joint (or any other component) fail. If the front of the driveshaft drops to the roadway, the vehicle attempts a "pole vault", usually with disastrous consequences.
From Mazda T2600 Workshop Manual 1989, page L-18

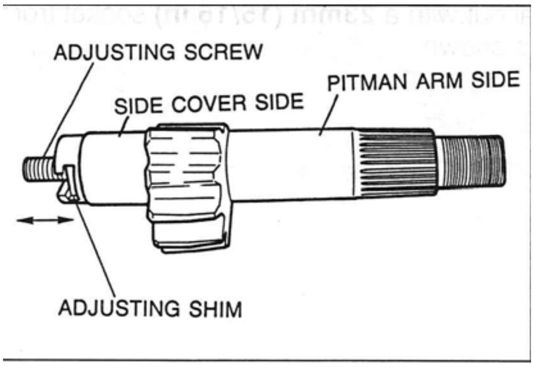


Figure 5-4 Although it oscillates only through 50-60° in order to steer the front wheels on a Mazda truck, this component from the steering box is described as a **SECTOR SHAFT**. It features part of a gear (a sector) which gives the shaft its name, and tapered splines onto which a lever called the **PITMAN ARM** is fitted tightly by tightening a nut on the right-hand threaded end.
Mazda T2600 Workshop Manual 1989 page N-20

Figure 5-5 A large component, referred to as a shaft, in a wind turbine.
A notable feature is the large flange which appears to have been formed by forging. The shaft has been machined all over after forging. It appears that this shaft acts as a pivot to allow the blade and generator assembly to turn to face the wind.
http://www.steelforgings.org/shafts/forgedsteelshafts.html

1.1.2 Axles

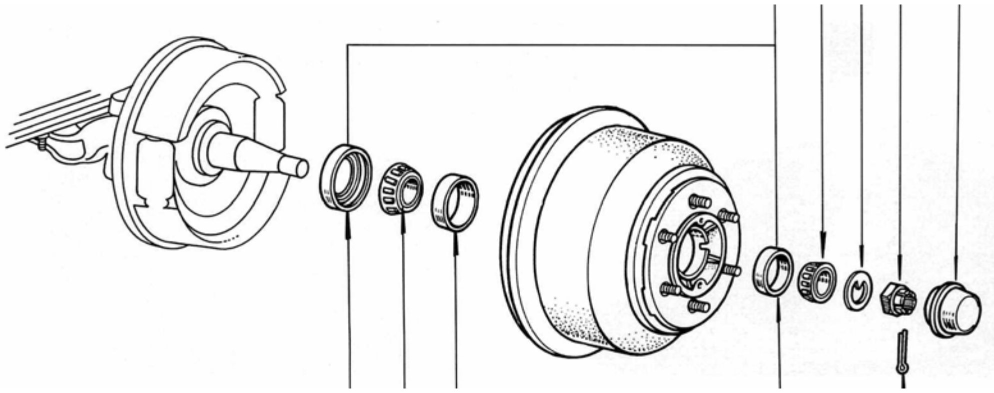


Figure 5-6 An exploded view showing the components which are assembled onto the **STUB AXLE** (on left of diagram) on the front axle of a Toyota light truck. The stub axle **assembly** is able to rotate say ±35° about a near-vertical **KING PIN** (not visible) to allow the front wheels to be steered but the stub axle does not rotate about its own axis. The front wheel rotates on **BEARINGS** mounted on the stub axle. In this assembly, **TAPERED ROLLER BEARINGS** (see Figs 5-39 and 5-40) have been used. See also Fig 5-7 below, which is a sectioned view of a stub axle and hub **ASSEMBLY**.
Toyota Dyna & Coaster Repair Manual, 1978, page 5-7

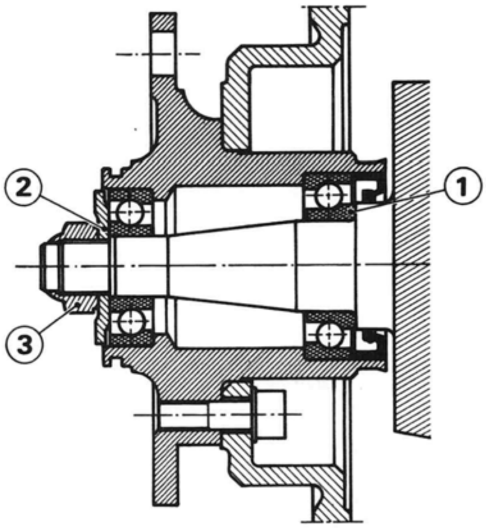


Fig. 11.7 Sectional view of front hub and ball bearings (Sec 3)

1 Inner race *3 Nut*
2 Thrust washer

Figure 5-7 An assembly of wheel hub and brake drum, two **ANGULAR-CONTACT BALL BEARINGS**, seal and securing nut on a **STUB AXLE**. The wheel rotates on the bearings – the stub axle does not rotate. **ANGULAR CONTACT BEARINGS** (see Fig 5-36) and **TAPERED ROLLER BEARINGS** (used in Fig 5-6) are both capable of resisting the “sideways” forces which are developed as vehicles travel around corners.
Mead, J S, Workshop Manual for Peugeot 504, Haynes, 1981, page 173

1.1.3 Spindles

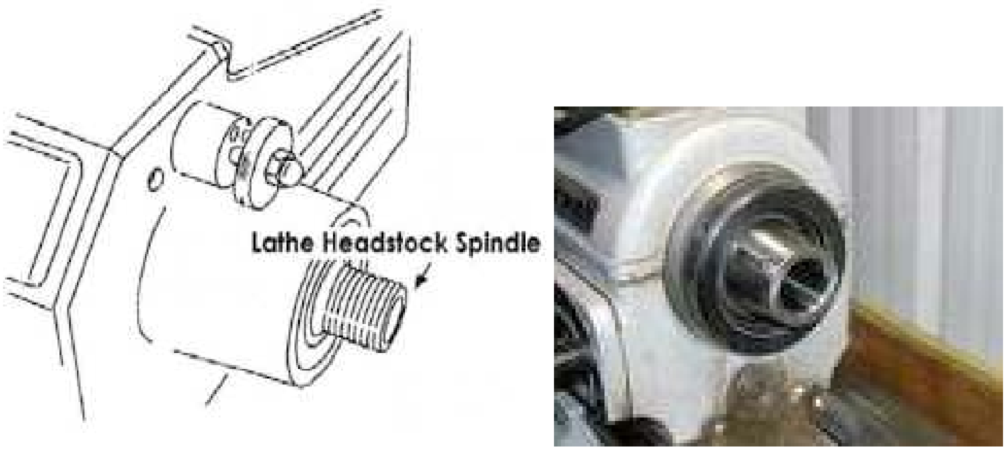


Figure 5-8 *Left:* Sketch of a **HEADSTOCK SPINDLE** in a lathe. The spindle rotates and has a threaded end onto which can be screwed a three- or four-jaw chuck. The work to be "turned" is clamped in the chuck.
Right: The protruding end of an actual **HEADSTOCK SPINDLE**. This spindle is hollow so that long bars can pass right through the headstock. This particular headstock has a tapered end onto which chucks, faceplates, etc may be mounted.
http://www.google.com.au/search?client=safari&rls=en&q=headstock+spindle+pictures

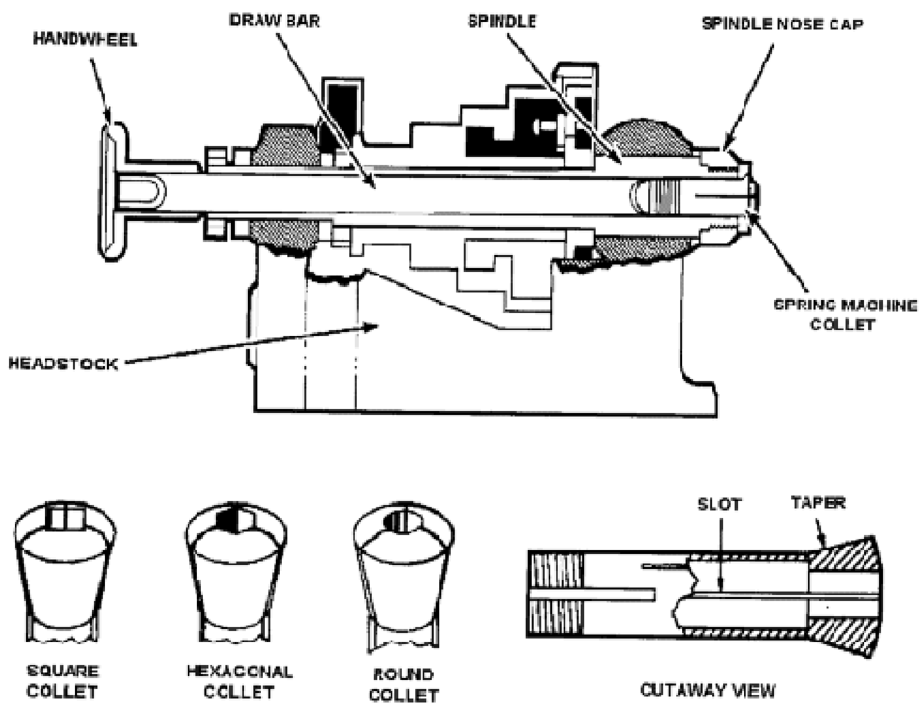


Figure 5-9 Sectioned drawing of a lathe headstock **SPINDLE**, this time with **COLLETS** for accurate mounting of small components.

http://www.google.com.au/search?client=safari&rls=en&q=headstock+spindle+pictures

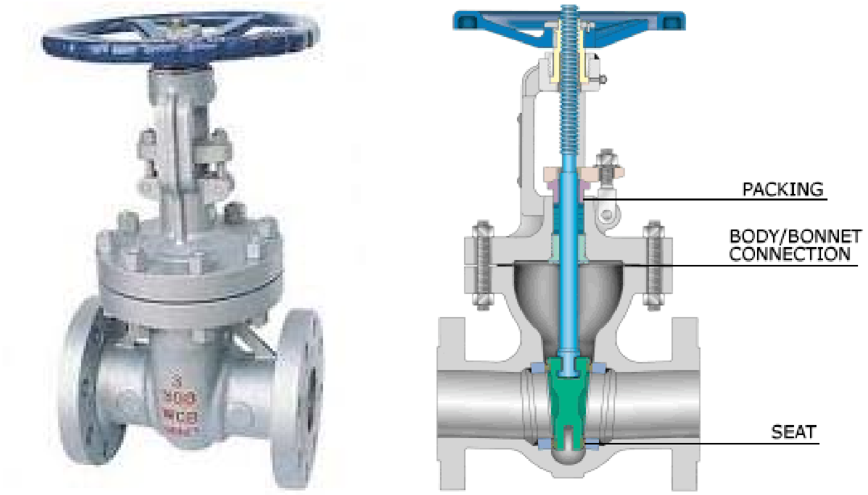


Figure 5-10 *Left:* A fully assembled **GATE VALVE**. *Right:* A sectioned view of a **GATE VALVE**, showing the **SPINDLE** (coloured blue) used to raise or lower the **GATE** (coloured green) to allow or block flow through the valve.
http://www.valvediagnostics.com/media/pictures/gate.gif

1.1.4 Stub shafts

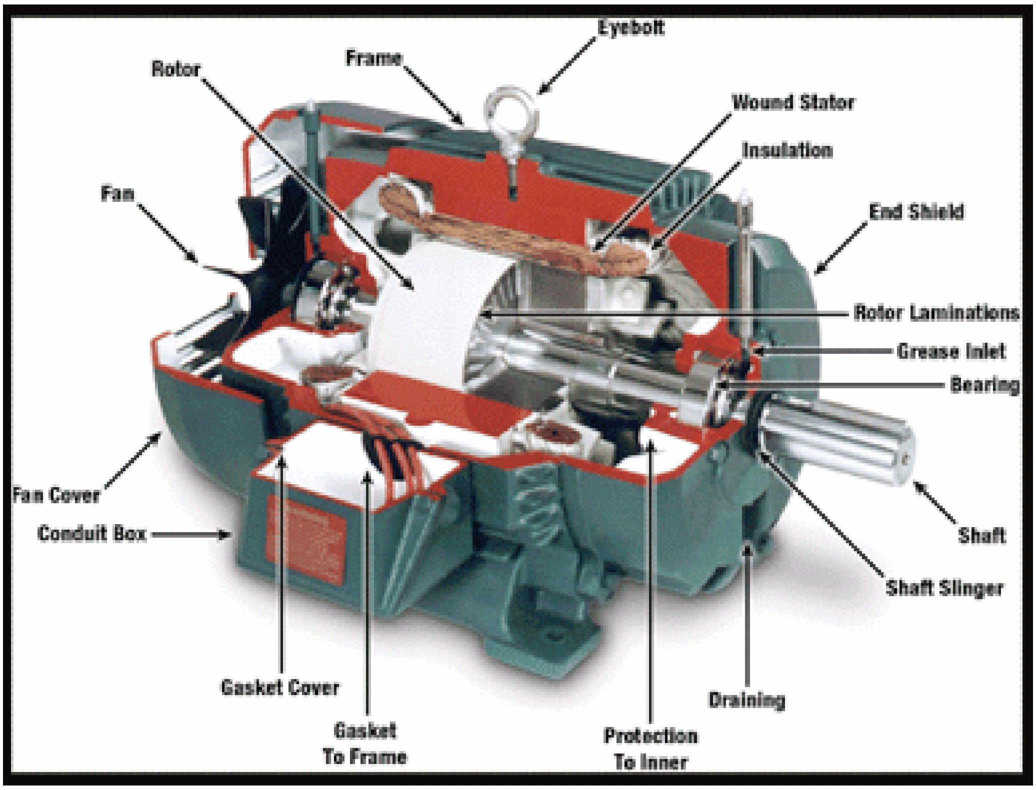


Figure 5-11 An electric motor showing the shaft protruding from the casing. This arrangement is referred to as a **STUBSHAFT**. It allows a power-transmission device such as a belt pulley to be fitted to drive an external machine. Note the two keys fitted (90° apart) to the stubshaft to prevent slippage of the pulley.

http://www.naw.co.za/motors_files/diagmotor.gif

1.1.5 Line shafts

Figure 5-12 In the days before OH&S! The overhead **LINE SHAFT** ran continuously and individual machines could be stopped only by moving the flat drive belts from the driving pulley onto a free-running pulley. Note the largely timber construction of the building, allowing significant flexing of the structures under load.
http://upload.wikimedia.org/wikipedia/commons/thumb/1/16/Line_shaft.jpg/400px-Line_shaft.jpg

1.1.6 Jack shafts

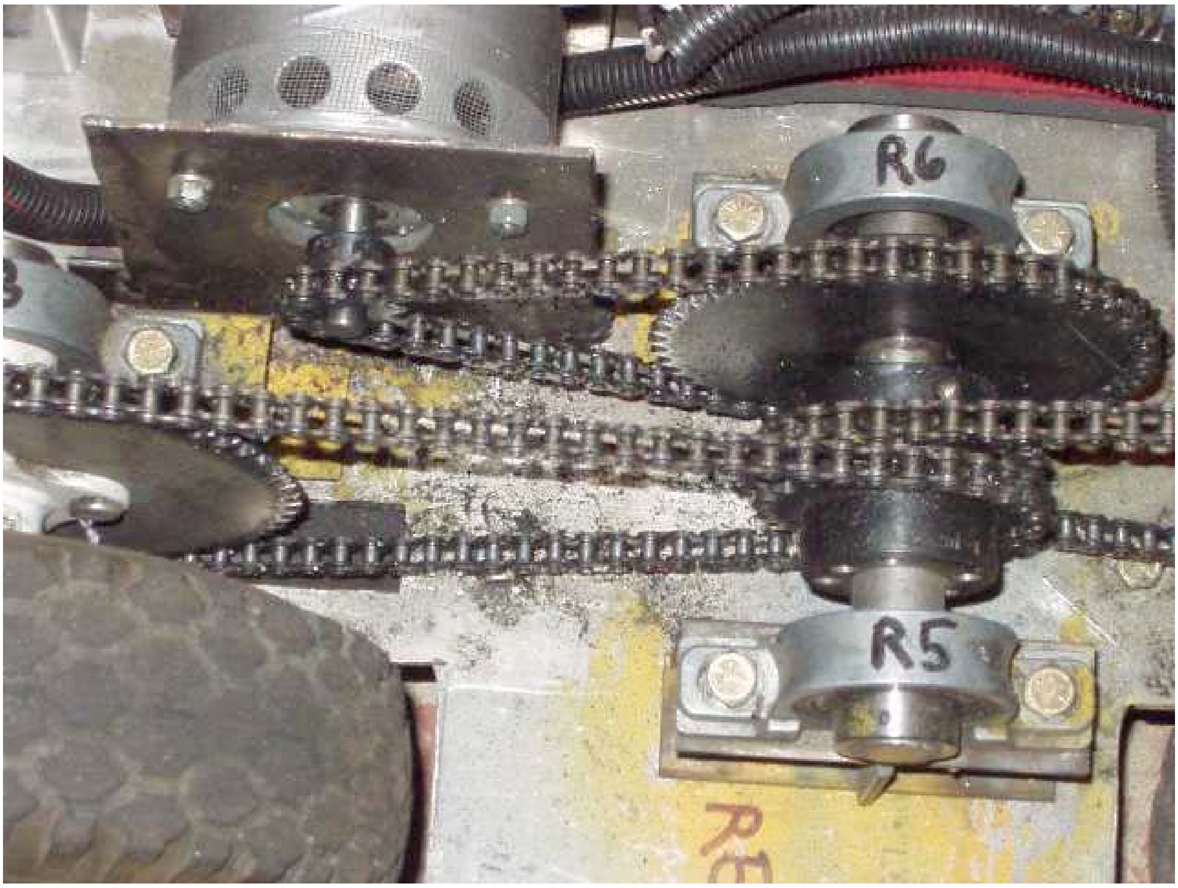


Figure 5-13 A shaft of the type seen on the right of this photograph is sometimes referred to as a **JACK SHAFT**. Its function in this figure is as part of a drive system to provide a decrease in rotational speed from the electric motor (at top left) to the jack shaft, then a second reduction in speed between the jack shaft and the two driven components (not visible). In this case, the drive is via **SPROCKETS** and **CHAINS**, although pulleys and belts might have served equally well. Note that the principles of speed reduction are similar to the gear drives discussed in Part 4 of these notes.The jack shaft is mounted on two plummer blocks (marked R5 and R6 respectively) which are of the type fitted with rolling contact bearings. Compare with the simple plain-bearing plummer blocks shown in Fig 5-24 below.
http://www.teamkiss.com/lunch/jackshaft.jpg

1.1.7 Flexible shafts

Figure 5-14 Japanese style backpack mower with flexible shaft between the red power pack and the usual hand-held mower assembly. In general, flexible shafts are not used to transmit high powers or high speed.
http://www.sz-wholesale.com/uploadFiles/Japanese%20style%20backpack%20mower%20with%20flexible%20shaft_600.jpg

1.2 Shaft materials

Most shafts are made from steel, either low- or medium-carbon. However, high quality alloy steel, usually heat treated, may be chosen for critical applications.

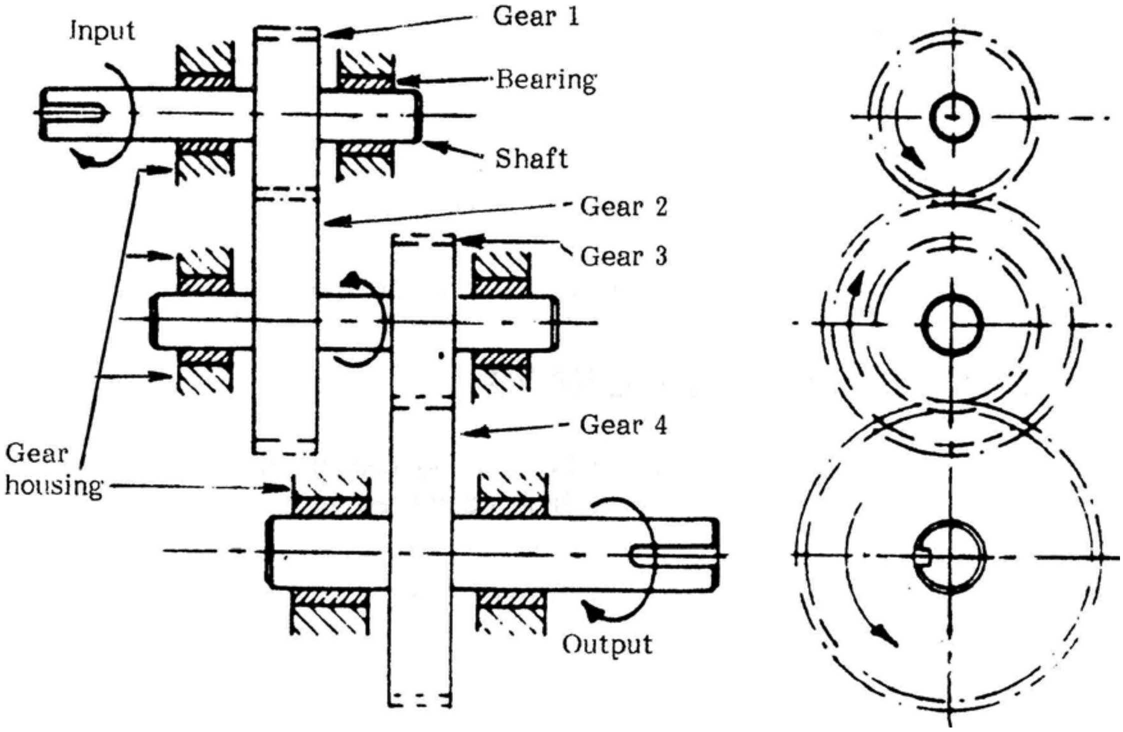
Other metals, e.g. brass, stainless steel or aluminium, may be used where corrosion is a problem or lightness is required.

Small, light-duty shafts, e.g. in household appliances, may be injection-moulded in a plastic material such as nylon or delrin.

1.3 Functions of shafts

- As previously noted, shafts transmit power. Since
  $$P = T\omega,$$
  this implies both **ROTATION** and the transmission of **TORQUE**.
- Shafts locate members such as gears and pulleys in their correct relative positions.
- Shafts connect members such as gears together and transmit torque from one member to another. In Figs. 5-15a and 5-15b, the intermediate shaft of the double reduction gear train transmits torque from one gear to the other on the same shaft. The input and output shafts transmit torque between the single gear on each of these shafts and some other component (such as a belt pulley or chain wheel) which will be mounted on the projecting end of the shaft. Note that these are simplified diagrams. In

practice, shafts usually have numerous changes in diameter to accommodate bearings, gears and other components mounted on them, as well as features such as keyways and splines (see later in this project) to provide torque transmission. Many such features are visible in Fig. 5-16, which is a sectioned elevation of a commercial vehicle gearbox.



Elevation view of gears, shafts, bearings and gear housing.

End view of gears and shafts. Other detail omitted.

Figure 5-15a An example of the use of shafts to mount the gears used in a double reduction (or compound) gear train. Note that while this simplified sketch shows shafts, the bearings which locate them, and the housing into which the bearings fit, there is no provision for axial location of the shafts. Note also the increased diameter of the output shaft, needed to transmit the increased torque created by the speed reduction. With two stages of gear reduction, the input and output shafts rotate in the same direction.

Reproduced from J. Carvill, *The Student Engineer's Companion*, Butterworths, 1980.

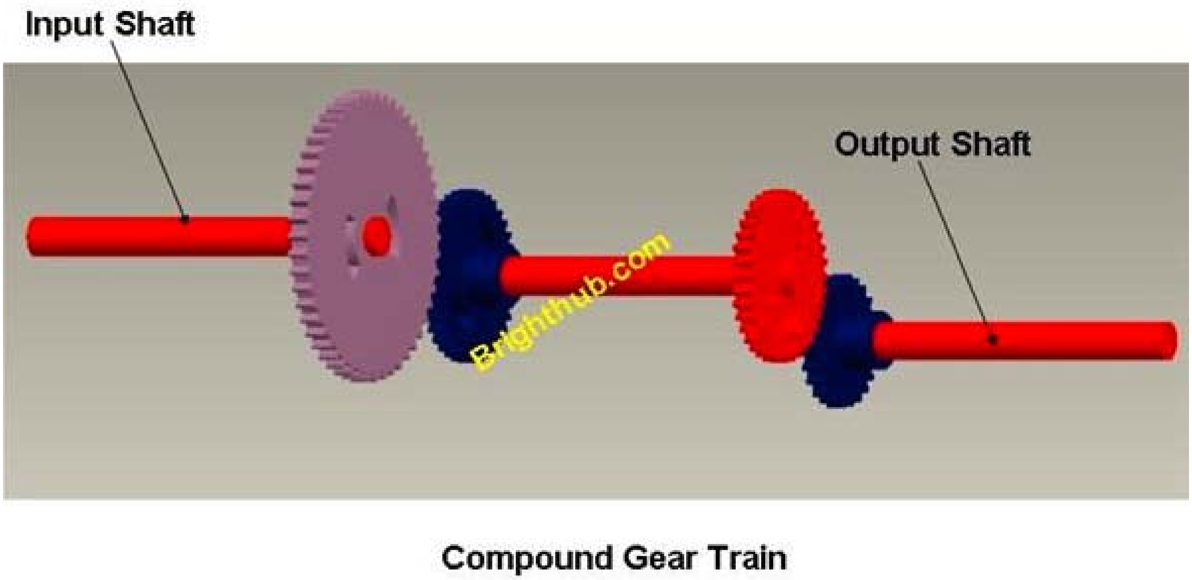


Figure 5-15b Repeat of Fig 4-34, showing the principle of a compound gear train. Refer to Part 4 Section 2.7 for explanation of the compound drive.
http://www.brighthub.com/engineering/mechanical/articles/66020.aspx?image=68312

FOR KEEN STUDENTS

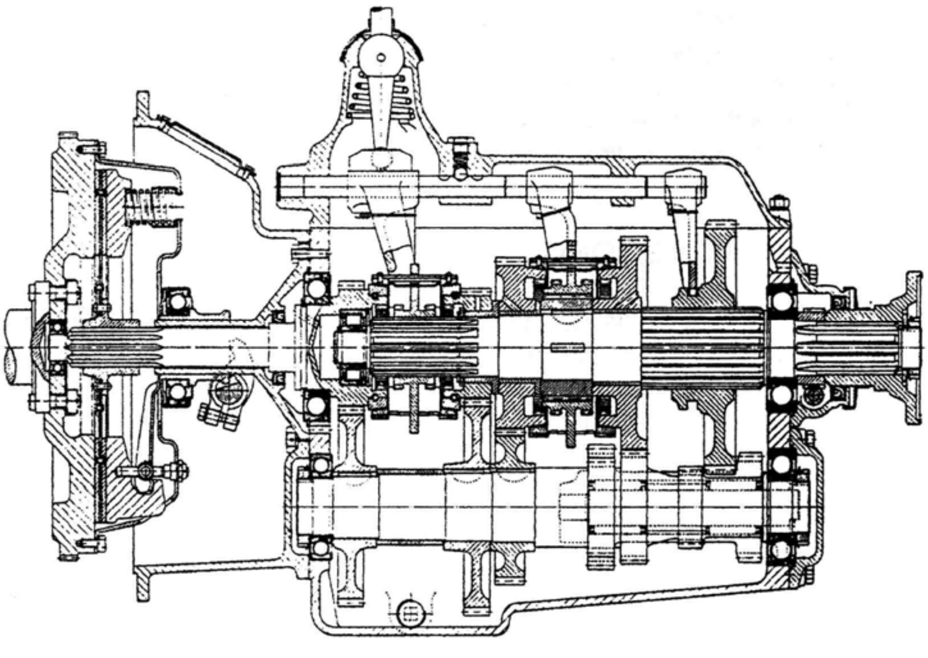


Figure 5-16 Commercial vehicle gearbox. This gearbox has three torque-transmitting shafts, showing typical configurations of diameter changes, splines, grooves and keyways, as well as seven rolling contact shaft bearings (including one cylindrical-roller bearing), at least two oil seals, three speed-change forks (four forward speeds plus reverse), a splined driving flange, a clutch assembly using helical coil compression springs, etc, etc.
Reproduced from SKF Typical Bearing Schemes, The SKF Ball Bearing Co. (Aust.) Pty Ltd, Melbourne. © AB Svenska Kullagerfabriken, 1962.

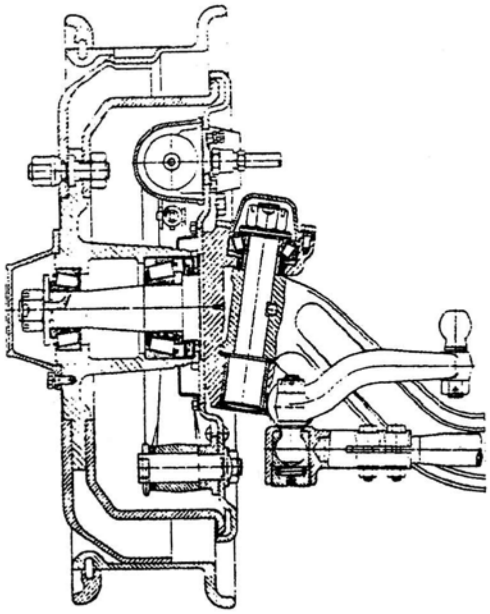


Figure 5-17 Commercial vehicle front wheel assembly, showing how the wheel hub is mounted through its two tapered-roller bearings onto the stub-axle, which does not rotate. The near-vertical king pin which allows the stub axle assembly to swivel for steering purposes is also visible. In this particular stub axle assembly, the upper bearing for the king pin has a tapered roller bearing to reduce steering effort.
Reproduced from SKF Typical Bearing Schemes, The SKF Ball Bearing Co. (Aust.) Pty Ltd, Melbourne.

1.4 Shaft bearings

As previously noted, shafts rotate. They must therefore be mounted in **BEARINGS** which

- Allow rotation.
- Reduce friction to a low level.
- Reduce wear of both shaft and bearings to an acceptable level.

Since shafts are often used to locate items such as gears in precise locations, **BEARINGS** must

- Have minimal clearance (or slack) between bearing and shaft.
- Locate the shaft both radially and axially.

The different types of bearings available will be described later in this project.

1.5 Transmitting torque to and from shafts

In many machine designs, torque must be transmitted between shafts and gears, pulleys, chain-wheels and other hubs. In almost all cases, this must be done without allowing slip between the two parts. As shown below, there are a number of ways in which this torque transfer may be achieved.

1.5.1 Keys

Perhaps the most widely used method of torque transfer is by the use of **KEYS**.

Keys transmit torque by the mechanism shown in Fig. 5-18. A longitudinal groove called a **KEYWAY** is machined into the shaft and a corresponding groove into the bore of the hub. The **KEY** fits simultaneously into both grooves, locking them together. The **KEY** is subjected to direct shear.

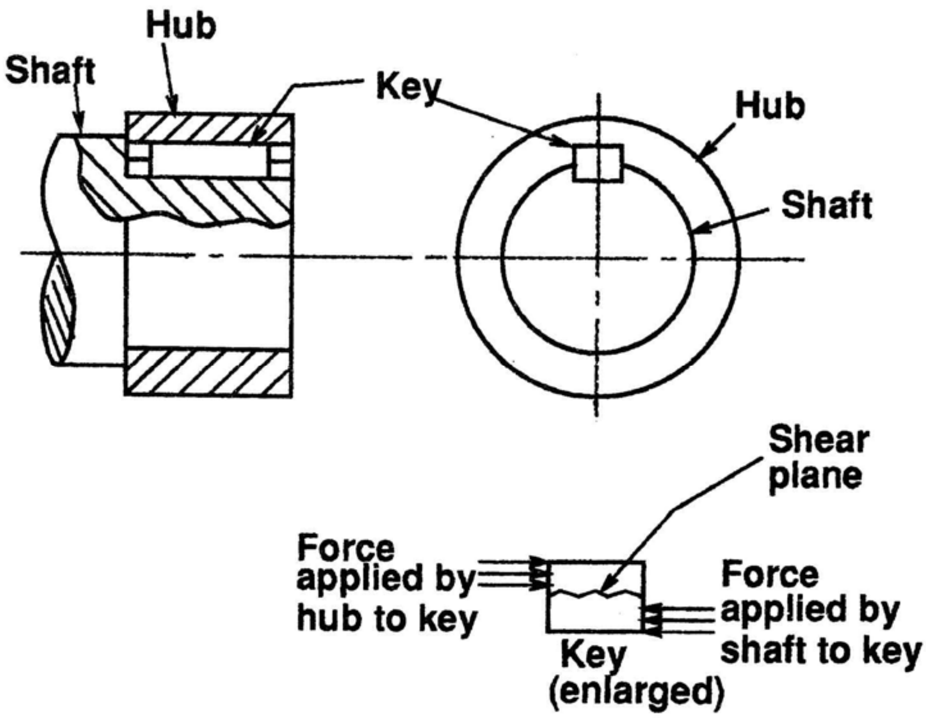
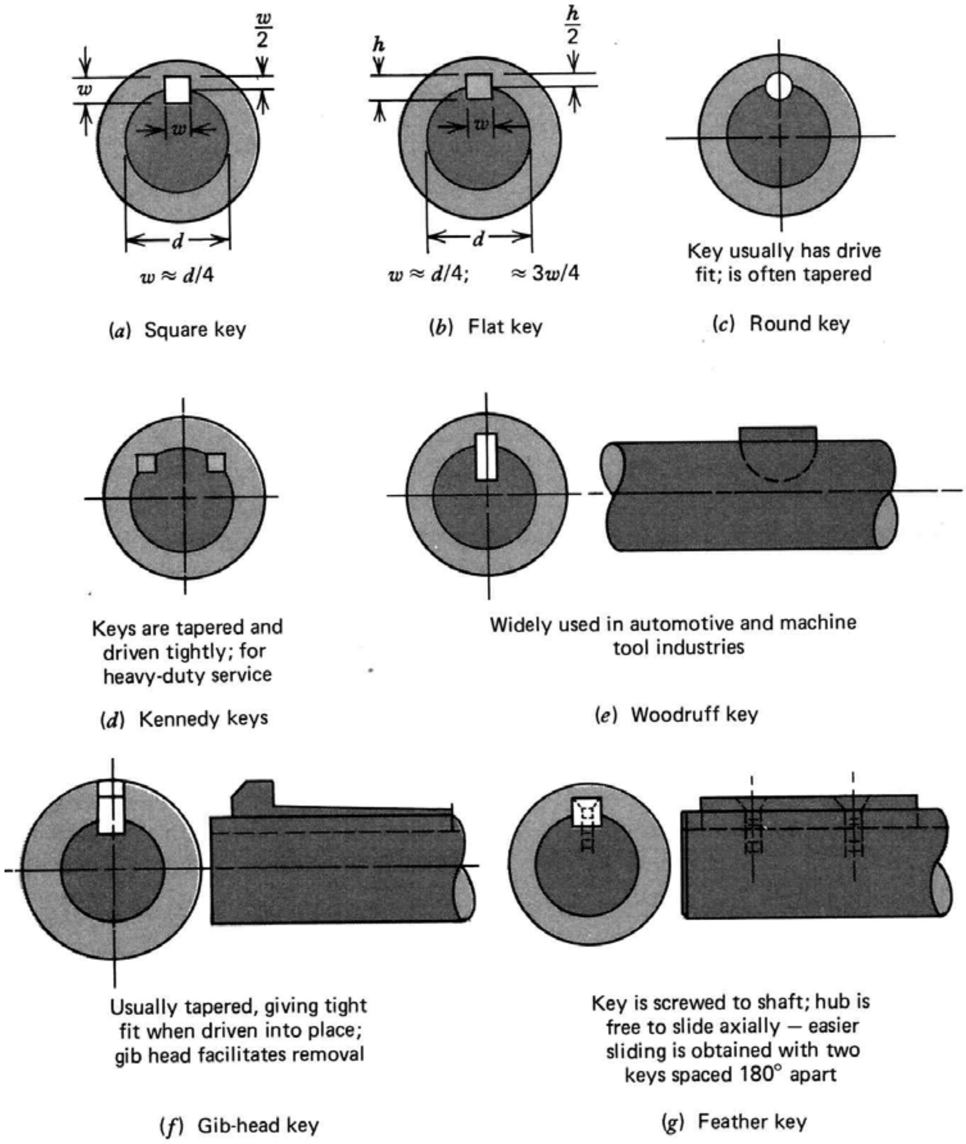


Figure 5-18 The principle of direct shear by which a key transmits torque from shaft to hub or vice versa.



Juvinall, R C, Fundamentals of Machine Component Design, Wiley, 1983, page 537

(h) Further details of feather keys and the profiled keyways into which they fit.
http://www.rinomechanical.com/feather-keys.htm

Figure 5-19 Examples of types of keys in general use, including the square key already illustrated in Fig 5-18. Note that the flat key (b) is incorrectly drawn – it should have a rectangular cross-section with the larger dimension resisting direct shear as shown in Fig 5-18.

Several shapes of key are in common use and keys are visible in numerous locations in Fig. 5-16. Note that, in general, keys **do not** provide axial location of the hub. In fact, feather keys are designed to allow the "hub" (in whatever form it is) to slide along the shaft. One exception is the gib-head key which is tapered and provides reasonable axial location when the key is hammered into place.

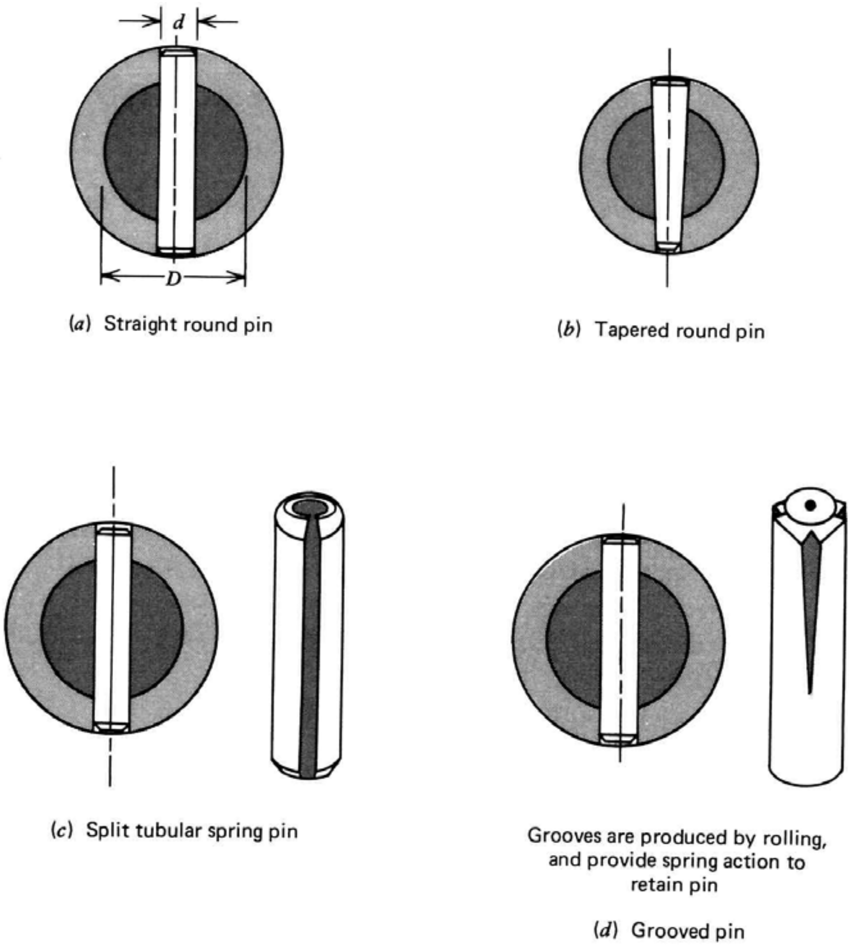


Figure 5-20 Round pins of various types are sometimes used in place of keys. Pins are generally regarded as suitable only for light duty.
Juvinall, R C, Fundamentals of Machine Component Design, Wiley, 1983, page 538

1.5.2 Grub screws and set screws

Refer to Part 2 of these notes.

These are regarded as light-duty attachments. Sometimes the end of the screw merely bears against the surface of the shaft. In other cases (dog-end or cone-end screws) the end of the screw may enter a drilled hole in the shaft, as in Fig. 5-21.

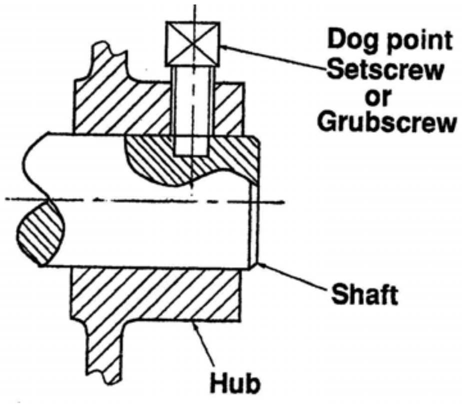


Figure 5-21 Transmission of torque by means of a set-screw or grubscrew. The end of the screw is subjected to direct shear, similar to the key in Fig. 5-18.

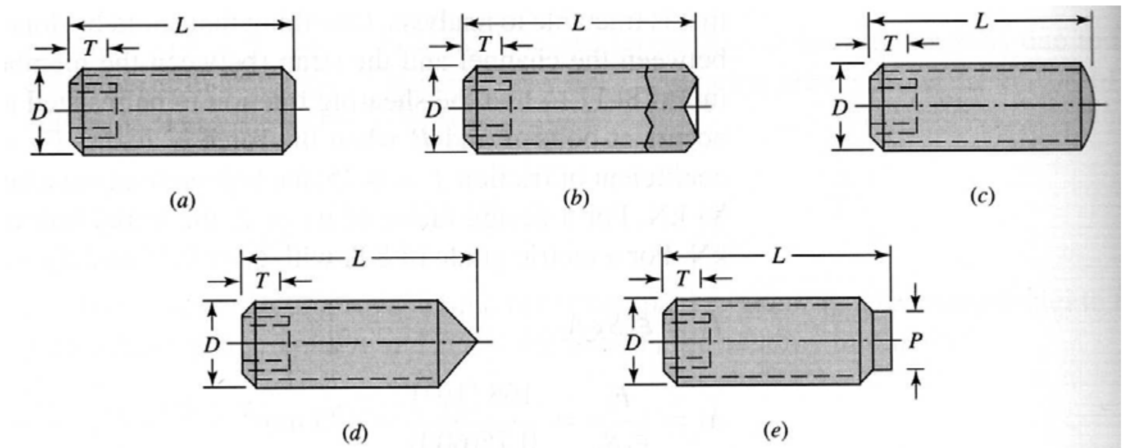


Figure 5-22 Drawings of different types of setscrews or grubscrews. In general, setscrews or grubscrews may have the internal hexagon shown in this figure and also Fig 5-23, or the square head seen in Fig 5-21, or even a screwdriver slot.
Shigley, J E, Mischke, C R, Mechanical Engineering Design, 6E, 2001, McGraw Hill, page 502.

Figure 5-23 Photographs of actual cone point, flat point and dog-point setscrews or grubscrews. http://www.stagonset.co.uk
http://www.hobbyparts.com.au/store/partslist/socketsetscrewsdogpoint/fasteners/popular/1/

1.5.3 Splines

SPLINES are essentially axial grooves or recesses which are machined into the shaft, very like a series of keyways. Splines are an integral part of the shaft (cf. keys, which are loose parts). Corresponding grooves are cut (**BROACHED**) into the bore of the hub so that the shaft/hub assembly forms a series of interlocking projections. The resulting connection is stronger than a keyed joint and is used in heavy-duty applications.

Spline profiles may be square, involute or triangular.

Splines are often designed to allow axial movement of a gear or hub whilst continuing to transmit torque. One particular application is in a multi-speed gearbox such as that seen in Fig 5-16. For axial sliding to occur satisfactorily, the bearing pressure on the faces of the spline must be low and good lubrication must be provided.

Figure 5-24 Examples of **SPLINED SHAFTS** with **SQUARE SPLINES**. All three are part of automotive drive shafts or similar applications. The larger diameter cylindrical section on the left-hand end of each shaft is intended to be welded into a steel tube which forms the central section of the driveshaft. Refer to Fig 5-3 above for a drawing of a complete automotive drive shaft.
http://www.gasgoo.com/auto-parts-trade/image-LLLOTSO/Spline-Shaft.html

Figure 5-25 An example of a splined shaft from an automotive transmission (or gearbox). Details are not clear, but these splines are probably of **INVOLUTE** form (i.e. of the same shape as the involute gear teeth introduced in Part 4), since **INVOLUTE SPLINES** are easier to machine and are stronger than the square splines in Fig 5-24.
http://www.fordmuscle.com/forums/transmission-articles/487117-31-spline-toploader-output-shaft-conversion.html

1.6 Shaft failure modes

A shaft may fail by:

- Excessive lateral deflection, which causes items such as gears to move laterally from their proper location, resulting in incorrect meshing.
- Torsional deflection, which destroys the precise angular relationship or "timing" between sections of a mechanism.
- Wear. Wear may take place on bearing surfaces (**JOURNALS**) or other contact areas, such as cams.
- Fracture. Unless the shaft was grossly under-designed, fracture usually occurs by **FATIGUE CRACKING**. This is discussed below.

1.6.1 Fatigue cracking

This course can offer no more than a very brief introduction to the complex area of **FATIGUE FAILURE**, which will be taken up again in later years of the engineering course. Since this is a design course, we are interested in:

- Recognising components, and specific sections of them, which may be prone to fatigue failure.
- Observing design methods to reduce the likelihood of fatigue failure.

1.6.1.1 The mechanism of fatigue cracking

Fatigue cracking occurs under conditions of **REPEATED LOADING** or **CYCLIC LOADING**. It is not the magnitude of the load **in itself** which causes the failure. It is the **CUMULATIVE** effect of many thousands, often millions, of repetitions of loading, or **LOAD CYCLES**, which result in **CUMULATIVE DAMAGE**.

1.6.1.2 Load cycles

Consider the shaft shown in Fig. 5-26.

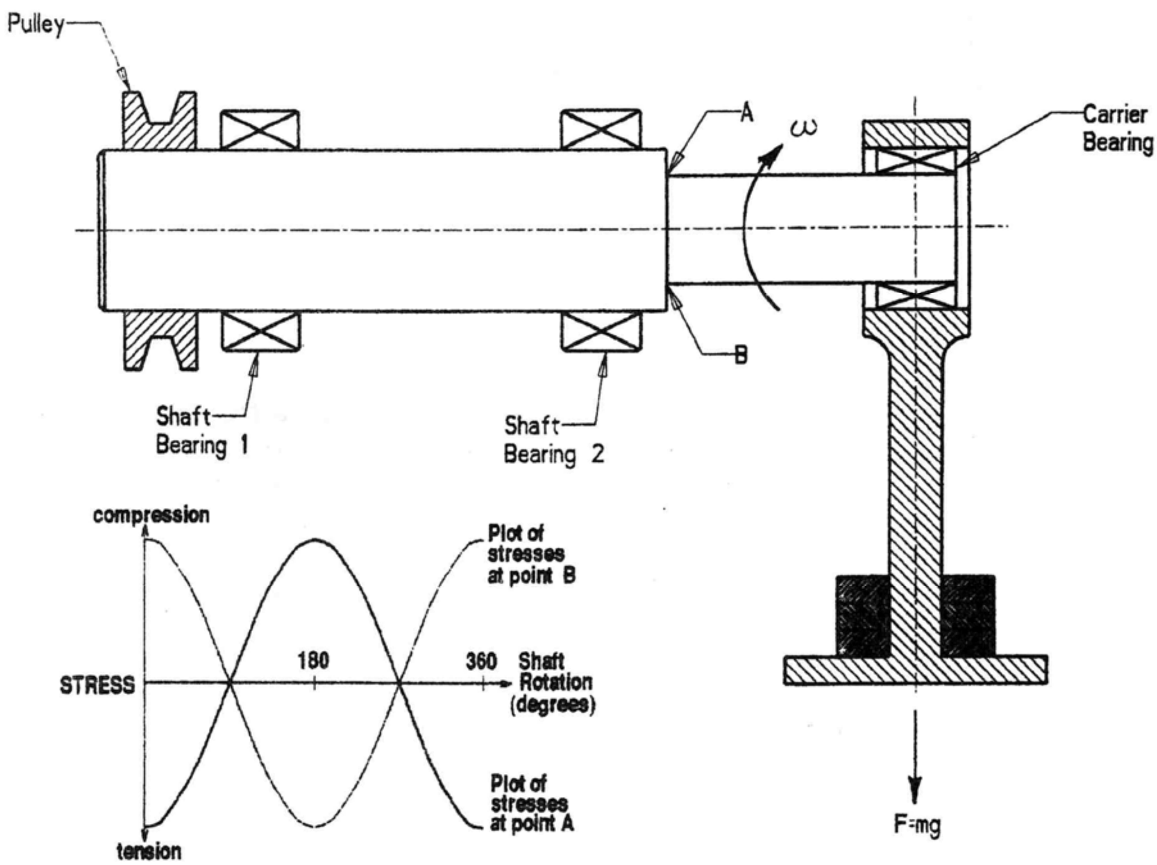


Figure 5-26 Schematic representation of cyclic loading of a rotating shaft subjected to a bending moment.

The shaft is mounted in two bearings which allow it to rotate with angular velocity ω, driven by the drive pulley at the left-hand end. A mass carrier at the right-hand end of the shaft is mounted on the shaft by another bearing. This bearing ensures that, as the shaft rotates, the mass carrier always hangs vertically downwards. It should be clear that the force due to the mass carrier is F = mg. This force applies a bending moment to the right-hand section of the shaft and the bending moment due to F reaches a maximum at Shaft Bearing 2.

Consider a point A at the top of the shaft. Since the force F is tending to bend the shaft downwards, the shaft material at A must be in **tension**. Similarly, the shaft material at a point B at the bottom of the shaft must be loaded in **compression**. Now let the shaft rotate through 180° so that point A moves to the bottom and B to the top. The shaft material at A is now in **compression** and the material at B is in **tension**. After a further shaft rotation of 180°, A is again at the top and in **tension**, while B is again at the bottom and is in **compression**. The total of 360° of shaft rotation results in one complete **LOAD CYCLE** for points A and B and, indeed, for all points on the shaft. Fig. 5-26 shows a graph of the load cycles for points A and B.

1.6.1.3 Fatigue crack propagation

Within certain limits, the application of large numbers of load cycles may cause tiny cracks to occur at highly stressed sections of the component. Subsequent load cycles cause this microscopic crack to increase in size, slowly at first, but with increasing rapidity. If not detected or checked in some way, the crack will eventually become so large, and will so weaken the component, that it will fracture completely. The final failure may be sudden and may have catastrophic consequences; nevertheless, fatigue cracking is a **PROGRESSIVE FAILURE** which has been occurring for some time prior to the final failure.

Due to the insidious nature of fatigue cracking and its potential to cause catastrophic failure, designers need always to be on guard against design features which may lead to fatigue failure. Items such as shafts which may undergo a very large number of rotations during their lifetime always need to be designed with fatigue failure in mind.

*For background only: It is generally accepted that fatigue cracking is caused essentially by **TENSILE** stresses. However, you need to be aware of the complexity of the stress fields in many engineering components. Shafts in pure torsional shear, for example, can fail by fatigue cracking, presumably due to normal (i.e. tensile) stresses acting along planes at 45° to the shaft axis.*

1.6.1.4 Stress concentrations

It is observed in practice that fatigue cracks frequently occur where there is a sharp or abrupt change in the shape of the component. Theoretical analysis and experimental techniques both show that stresses within the material rise sharply at abrupt changes of section. Such features are referred to as **STRESS CONCENTRATIONS** or **STRESS RAISERS**.

Referring again to Fig. 5-26, it is seen that there is an abrupt change of shaft diameter close to Bearing 2. This change in diameter is described as a **SHOULDER** on the shaft. Such a shoulder causes a significant **STRESS CONCENTRATION**. The location of the shoulder is already in a region of high bending moment and therefore of high tensile and compressive stresses. The combination of the two factors makes that cross-section of the shaft particularly vulnerable to fatigue failure. Note that in Fig 5-26, the maximum bending moment on the shaft actually occurs at Bearing 2, but the smaller shaft diameter and stress concentration due to the shoulder make this the cross section at which fatigue failure will occur.

Changes of cross-section other than shoulders which cause stress concentration effects in shafts include:

- Keyways
- Splines
- Circlip grooves
- Threads
- Oil holes
- Undercuts

1.6.1.5 Reducing stress concentrations

As designers, we need to understand that the potential for stress concentrations to produce fatigue cracking can be reduced in two ways.

- Reduce the stress-concentration effect by making the change of shape more gradual.
- Relocate the stress concentration or change of shape to an area subjected to lower stresses.

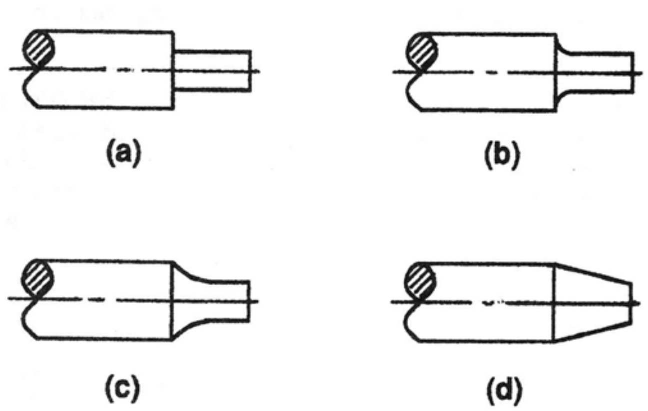


Figure 5-27 Methods of reducing stress concentration at a change of shaft diameter. Stress concentration effects **decrease** from (a) to (d).

Fig. 5-27 shows four ways of designing a change of shaft diameter. The sharp shoulder in (a) produces a very high stress concentration. The shoulder with **FILLET RADIUS** (b) is significantly better, the larger fillet radius (c) is better again and the long taper has a very low stress concentration.

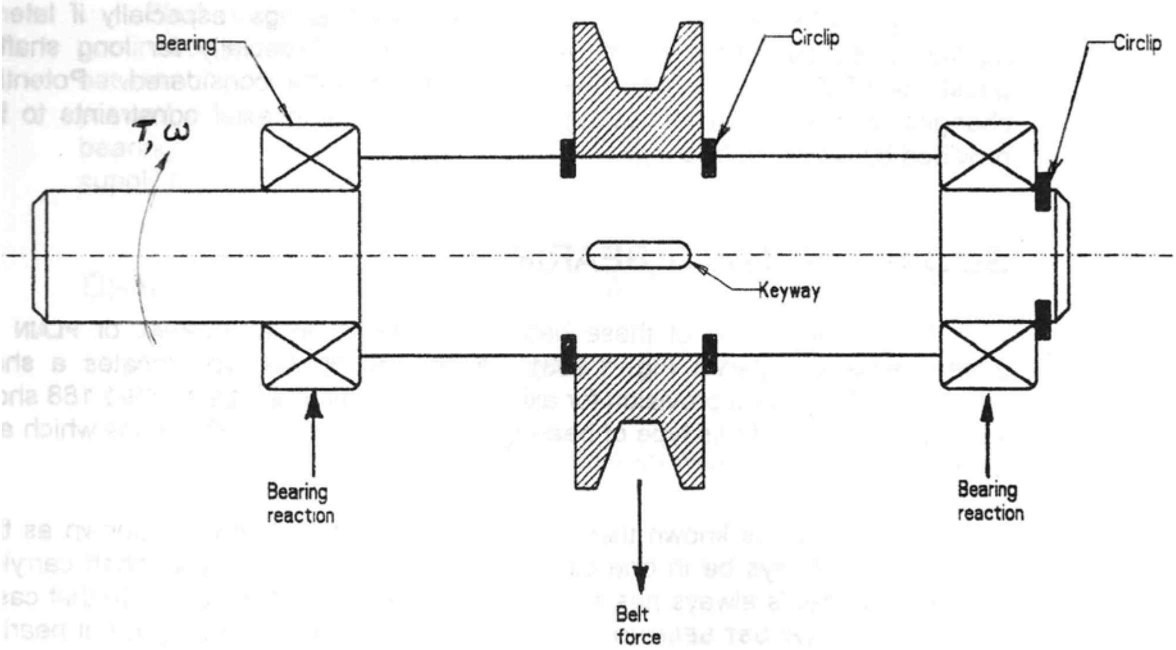


Figure 5-28 The effect of a stress concentration on shaft fatigue life depends on its location on the shaft. The circlip grooves on either side of the central pulley are in a location of high stress and seriously weaken the shaft. The circlip groove on the right-hand bearing is in an unstressed location and will have no effect on shaft life.

In Fig. 5-28, the centre pulley is mounted mid-way between the bearings. Due to the belt force on the pulley, the central section of the shaft is subjected to high bending moments causing high bending stresses. The left-hand section of the shaft also transmits torque and is subjected to torsional stresses. In this figure, the pulley is located axially by means of two circlips. The circlip grooves which must be machined into the shaft cause abrupt changes of section and are known to cause high stress concentrations. The keyway which must be used to transmit the torque between the pulley and the shaft also forms a severe stress concentration. Furthermore, the circlips and the keyway significantly reduce the cross-section of the shaft available to carry bending and torsion. This combination leads to a high risk of fatigue cracking and the design should be changed. On the other hand, the right-hand shaft bearing has been retained axially by a circlip and this circlip groove is in an unstressed region at the end of the shaft (no bending, no torque) so that the circlip may be used without the risk of causing fatigue cracking.

2 Bearings

Some of the requirements of **BEARINGS** were set out earlier in this project, when shaft location was discussed. Bearings may be classified in a number of different ways. However, for our purposes, it is sufficient to use two groups:

- Sliding contact
- Rolling contact

Before moving on to consider these two groups, it is worth pointing out the necessary conditions for stable and adequately constrained mounting of a shaft. Whilst being free to rotate, the whole shaft must generally be constrained against **RADIAL** movement and against **AXIAL** movement. In general, adequate radial constraint requires two bearings, relatively widely spaced along the length of the shaft. Only in the case of **very** short shafts should the use of only one bearing be considered. Again in general, the shaft will need axial restraint in two directions. Sometimes both axial restraints are applied by one bearing; in other cases, each of two bearings may provide restraint in one axial direction.

Long shafts usually require more than two bearings, especially if lateral rigidity (small deflection under load) is required. Especially for long shafts, questions of axial expansion due to heating must be considered. Potential changes of the length of either the housing or the shaft (or both) due to heating while in use usually require both axial constraints to be provided by the same bearing.

2.1 Sliding contact bearings

The simplest type of these bearings is known as a **JOURNAL** or **PLAIN** or **SLEEVE BEARING**. A bearing of this type locates a shaft **RADIALLY**. There is no provision for axial location. Fig 5-29 shows two examples of this type of bearing and the different constructions which are available.

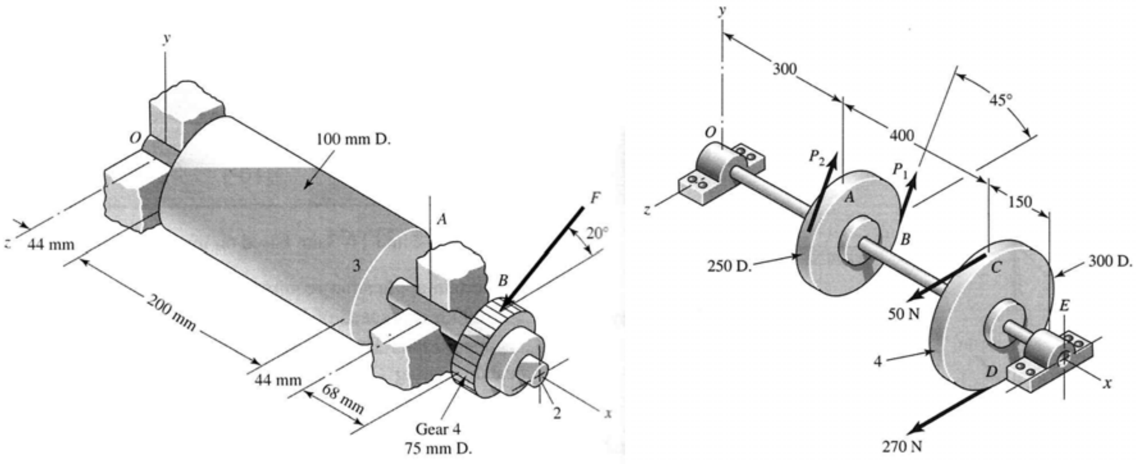


Figure 5-29 Examples of journal bearings. *Left:* The shaft simply runs in holes in the structural members of the machine, which may be steel or cast iron. *Right:* The shaft runs in separate components of the general style known as **PLUMMER BLOCKS**. Plummer blocks are usually fitted with **BUSHES** made from a material which has good wearing properties, such as bronze. The advantage in using bushes is that the **BUSH** can be replaced when it becomes worn. See Fig 5-30 below for examples of bushes.

Shigley, J E, Mischke, C R, Mechanical Engineering Design, 6E, 2001, McGraw Hill, page 730-731.

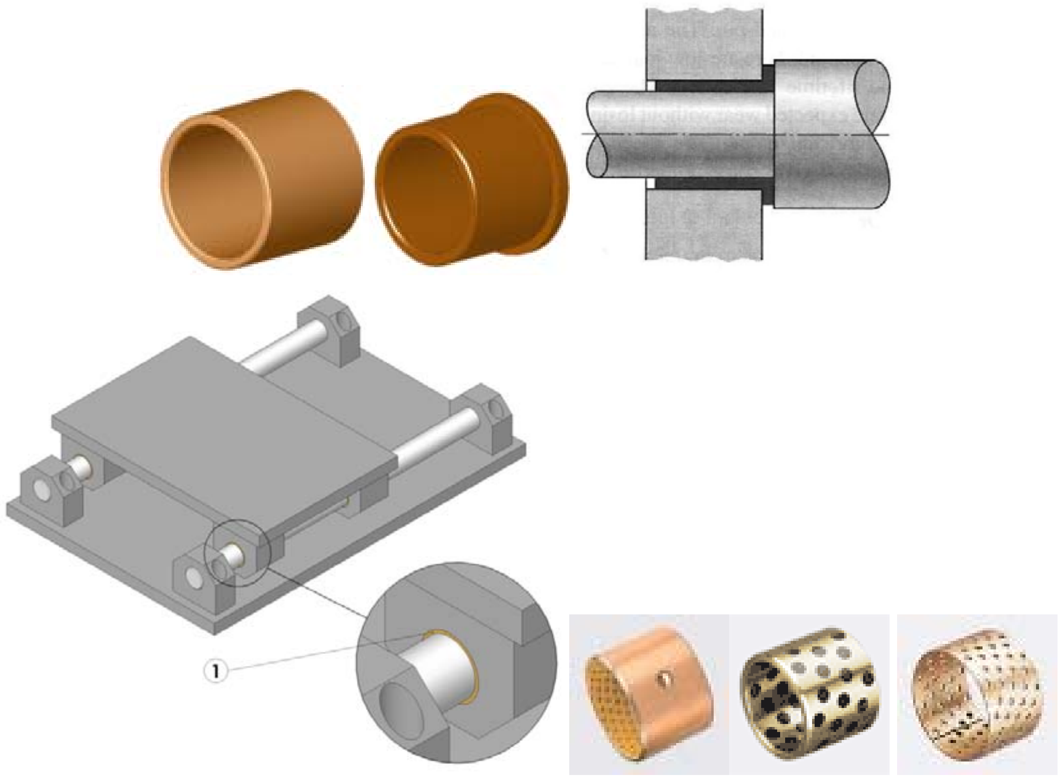


Figure 5-30a Examples of bushes and their application. *Top left:* A **PLAIN BUSH** which does not provide axial location, and a **FLANGED BUSH**. *Top right:* A shoulder on a shaft can be designed to contact the flanged bush to restrict the shaft's axial movement in one direction. *Bottom left:* Although it is usual to use bushes on rotating shafts, four **PLAIN BUSHES** have been used in this example to provide precise sliding movement of the platform relative to the base. *Bottom right:* Examples of bushes with provision for lubrication.
http://en.wikipedia.org/wiki/Plain_bearing http://www.sbs-bearings.com.sg/

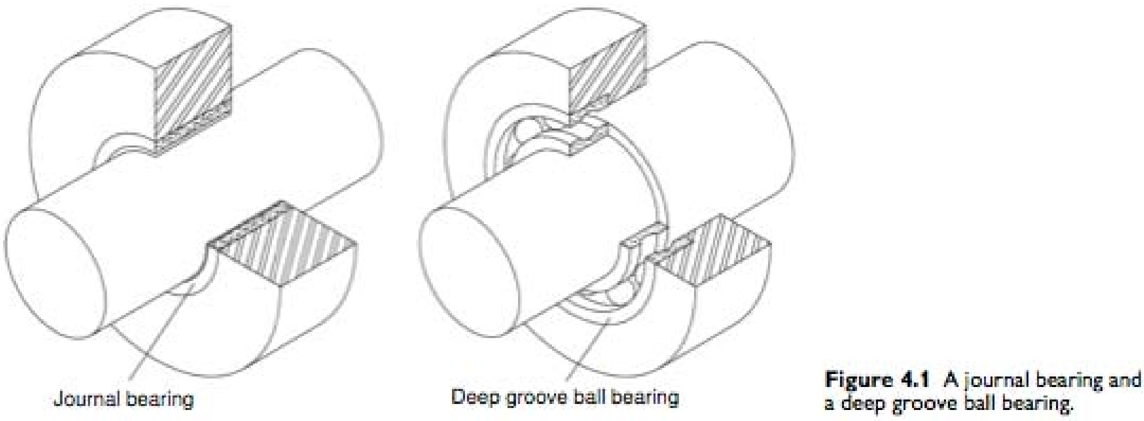


Figure 5-30b Comparison of the configuration of a bush type bearing with a rolling contact bearing. More detail of rolling contact bearings appears in later figures. http://www.scribd.com/doc/28723605/Mechanical-Design

FOR KEEN STUDENTS

Sometimes it is known that the **AXIAL FORCE** on a shaft (also known as the **THRUST**), will always be in one direction. For example, a vertical shaft carrying heavy components always has a thrust acting vertically downwards. In that case, one **FOOTSTEP THRUST BEARING** and one plain journal bearing will adequately locate the shaft. In the general case, where the direction of thrust may vary, two **PLAIN THRUST BEARINGS** will be required.

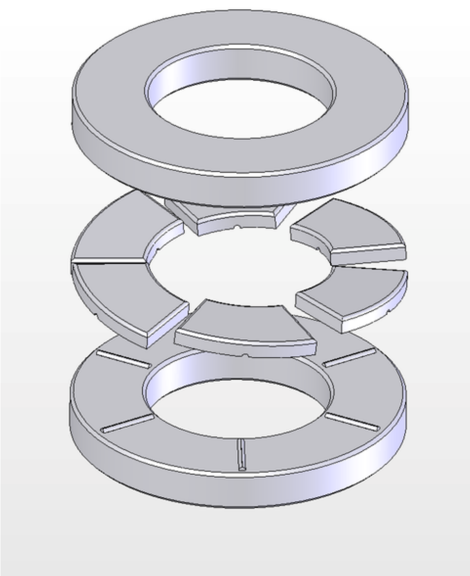


Figure 5-31 *Left:* Diagrammatic illustration of a thrust bearing which is designed to carry high axial loading. The lower ring is in contact with the structure and does not rotate. The upper ring rotates with the shaft. The concept is that the six segments between the upper and lower plates are free to tilt, thereby creating a wedge of lubricant which holds the moving surfaces apart and prevents wear. *Right:* A **TILTING-PAD THRUST BEARING** of the type invented by AGM Michell, an Australian engineer, and still widely used on the propeller shafts of large ships.
http://en.wikipedia.org/wiki/File:Fluid_thrust_bearing.PNG and
http://www.johncrane.co.uk/Prod_ProdPage_Layout

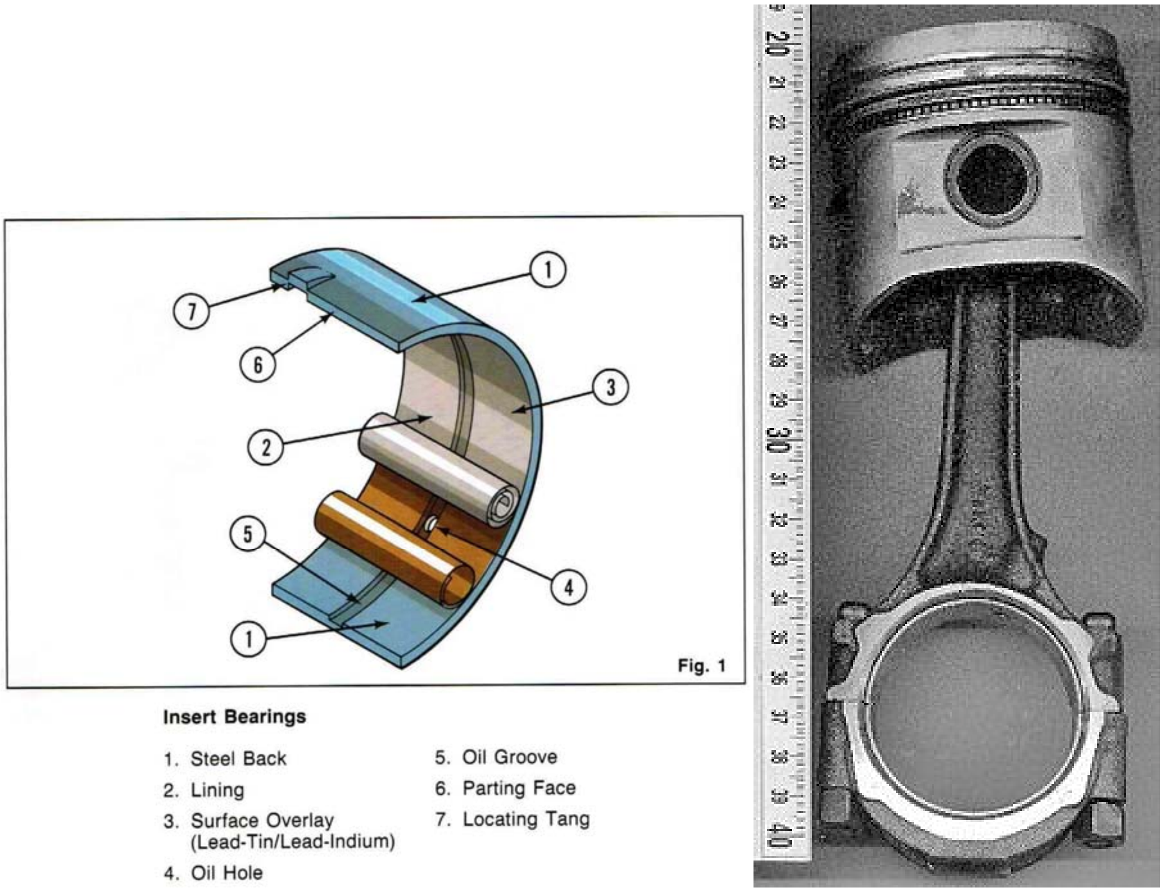


Figure 5-32: *Left:* An important class of plain bearings is the **SLIPPER BEARING** or **INSERT BEARING**, almost universally used for automotive engine bearings. Two semi-circular insert bearings are used to form the complete bearing. Note the steel backing or shell, the lining which forms the main load-carrying section of the bearing and the thin surface overlay of softer material for reduction of friction and quick 'bedding-in' of the bearing.
Cummins Engine Company Inc, Analysis and Prevention of Bearing Failures, Bulletin No 3810387-00 8/88
Right: The reason for using two bearing halves is clear from the photograph of the connecting rod and piston assembly – the **BIG END BEARING** at the bottom of the connecting rod must be assembled in the engine with the big end bearing on the crankshaft. This can be done only if the bearing can be separated into two halves for assembly purposes.
http://en.wikipedia.org/wiki/Connecting_rod

2.1.1 Materials for plain bearings

Where rubbing contact occurs between two machine parts, it is usual to make the parts of dissimilar materials. In the case of journal bearings, the shaft to be supported is almost always made from carbon steel, so bearings are seldom made of steel. Frequently used bearing materials are:

- Bronze, usually in the form of a bush; see Fig 5-30.
- White metal, a tin/antimony/copper alloy which is often bonded to a steel shell.
- Copper/lead/indium, often used for automotive engine bearings, usually bonded to a steel shell. See Fig 5-32
- Cast iron, with a shaft running directly in a machined bore in the cast component. See Fig 5-29 left.
- Various plastics such as PTFE, nylon, delrin.

2.1.2 Lubrication of plain bearings

Plain bearings are usually lubricated by grease or oil, supplied by an oil drip lubricator or a ring oiler or by periodic application of an oil-can.
Alternatively, it is possible to design a plain bearing as an air- or gas-lubricated bearing, which requires a constant supply of gas under pressure. Gas-lubricated bearings are beyond the scope of these notes.

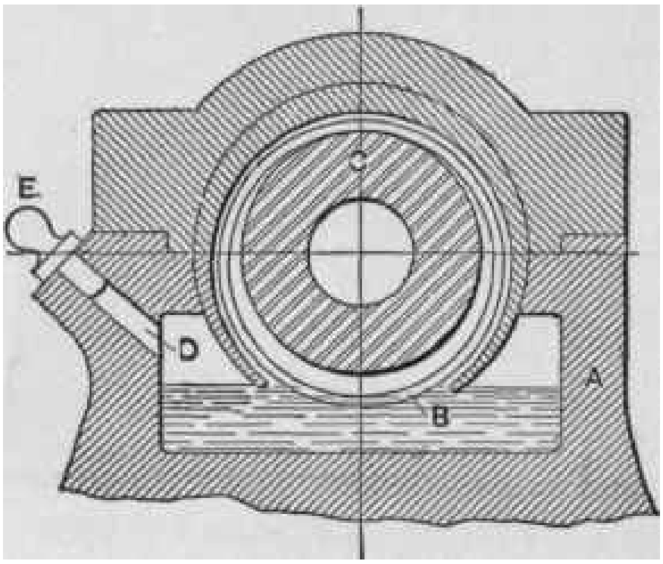


Figure 5-33 *Left:* An **OIL DRIP LUBRICATOR** in which the bowl is filled with oil and is set to drip oil at a predetermined rate into the bearing.
http://www.summit-tool.com/pcat-gifs/products-small/drop-sight-feed-iol.jpg
Right: Schematic of a **LOOSE RING OILER**. The lower part of the **LOOSE RING** (B) dips into the oil bath (A) and drags oil to the top of the bearing (C). Oil is replenished when necessary through (D).
http://chestofbooks.com/home-improvement/woodworking/American-Lathe-Practice/images/Fig-82-Loose-Ring-Oiler.jpg

Plain bearings in heavy-duty applications require lubrication by a continuous **FLOW** of oil under **PRESSURE**. The pressure helps to create a film of oil between the two metal surfaces. Also, by conducting away heat, the oil flow provides an important cooling function to prevent overheating of the bearing. One well-known example of this type of lubrication is the crankshaft bearings of virtually all car engines (Fig 5-32). These bearings fail very rapidly if the oil supply fails for any reason.

2.1.3 Characteristics of plain bearings

- Friction is higher than for rolling-contact bearings. Starting friction of plain bearings is significantly higher than running friction.
- Well-designed plain bearings can have an extremely long life. However, they can fail without warning.
- Plain bearings run more quietly than rolling-contact bearings.

2.2 Rolling contact bearings

These bearings use elements such as balls or rollers to avoid sliding contact. The usual practice is to provide two more-or-less cylindrical housings or **RACES**, the inner one of which fits onto the shaft and rotates with it, while the outer race fits into the fixed or non-rotating component. The rolling members (balls or rollers) run freely between the two races. In practice, it is impossible to achieve pure rolling and there will always be some sliding movement within the bearing. Despite this, such bearings run very freely and are often referred to as **ANTI-FRICTION BEARINGS**.

2.2.1 Ball bearings

2.2.1.1 Deep groove ball bearings

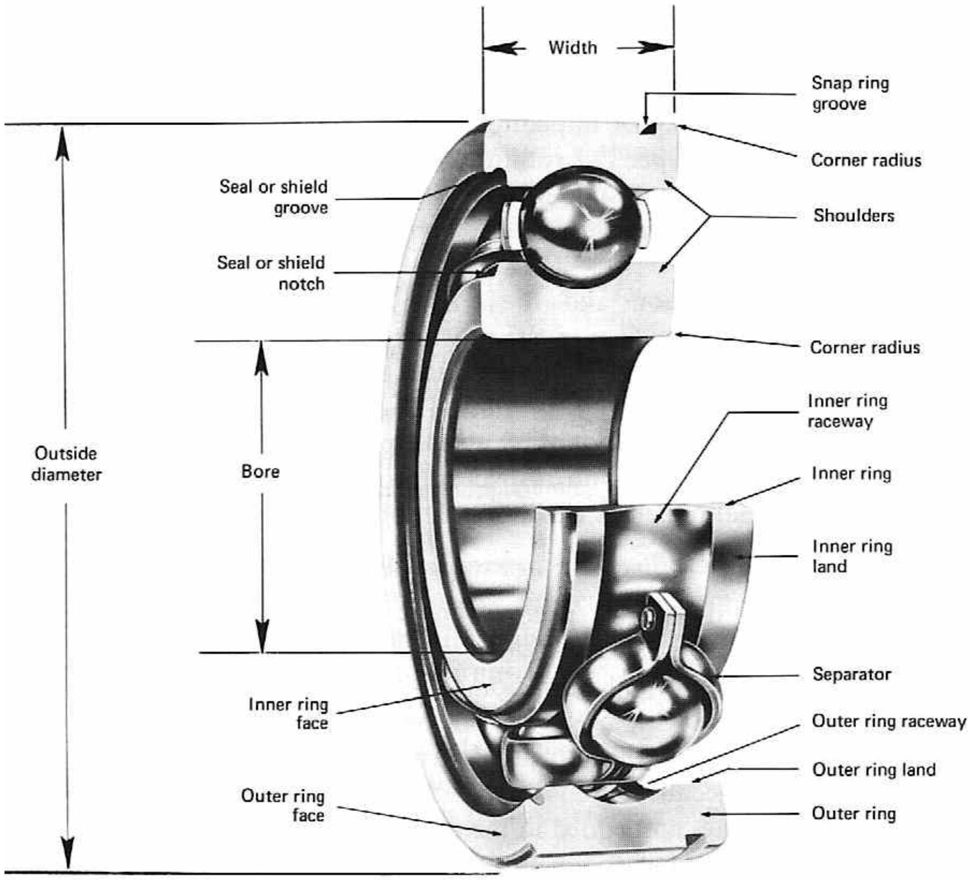


Figure 5-34 Ball bearing terminology.
Courtesy of New Departure-Hyatt Bearings Division, General Motors Corporation.
Reproduced from Deutschman, Michels & Wilson, *Machine Design*, MacMillan, 1975, page 445.

In ball bearings in general, the rolling elements are spheres of high quality, hardened and polished alloy steel, rolling in hardened alloy steel **INNER** and **OUTER RINGS** or **RACES**.

Fig. 5-35 shows how the commonly used **DEEP-GROOVE BALL BEARING** is assembled. After the maximum number of balls has been inserted between the **INNER AND OUTER RACES**, the balls are uniformly spaced around the races by a **CAGE** which is riveted into place as the last step in the assembly process. As well as spacing the balls, the cage performs the essential function of preventing the balls from contacting each other, which would cause scuffing and rapid wear. However, there remains some sliding contact and consequent friction between the balls and the cage, so lubrication is essential for long life.

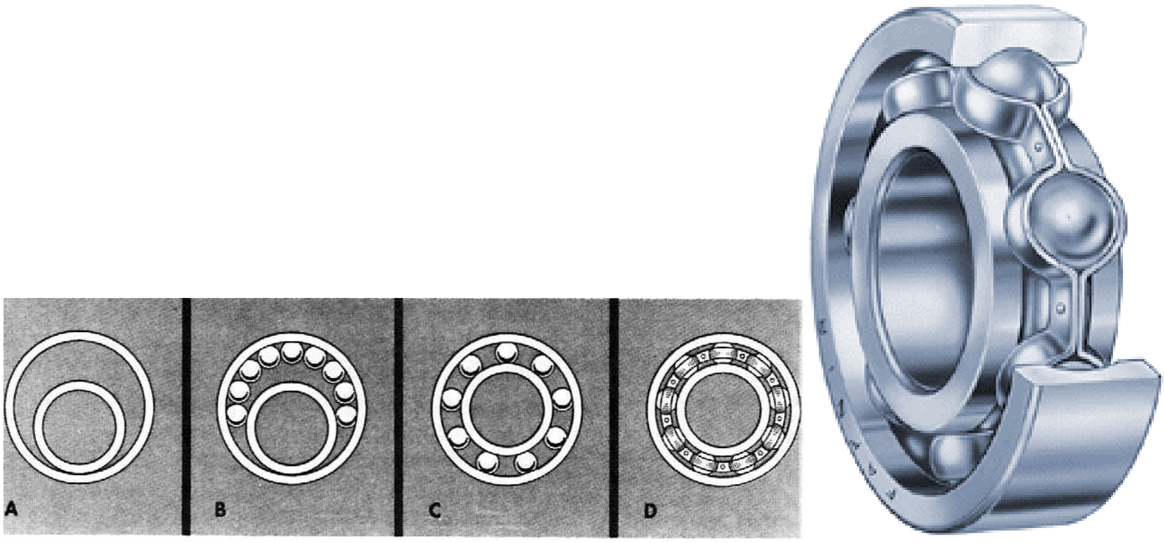


Figure 5-35 *Left:* Steps in the assembly of the **CONRAD** or **DEEP GROOVE** type ball bearing.
Courtesy of New Departure-Hyatt Bearings Division, General Motors Corporation.
Reproduced from Deutschman, Michels & Wilson, *Machine Design*, MacMillan, 1975.
Right: Sectioned view of an assembled deep groove ball bearing.
Courtesy The Timkin Company, at http://science.howstuffworks.com/bearing3.htm

An alternative to **DEEP GROOVE BALL BEARINGS** is the **FILLING NOTCH BALL BEARING**, in which small "notches" are cut out of one side of the inner and outer races. When the notches are aligned, the required number of balls may be slipped into the raceways before being spaced by the cage, as for the deep groove bearing. However, the notches create a slight discontinuity in the path of the balls, tending to decrease the life of the bearing.

Since in deep-groove bearings the balls run in shallow grooves in the races (Figs. 5-34 and 5-35), these bearings are able to support some axial loading as well as radial. Where greater axial thrust is expected, angular contact ball bearings such as those in Fig 5-36 are preferred and, where the expected load is entirely axial, a ball thrust bearing, illustrated in Fig. 5-37, may be used.

2.2.1.2 Angular contact ball bearings

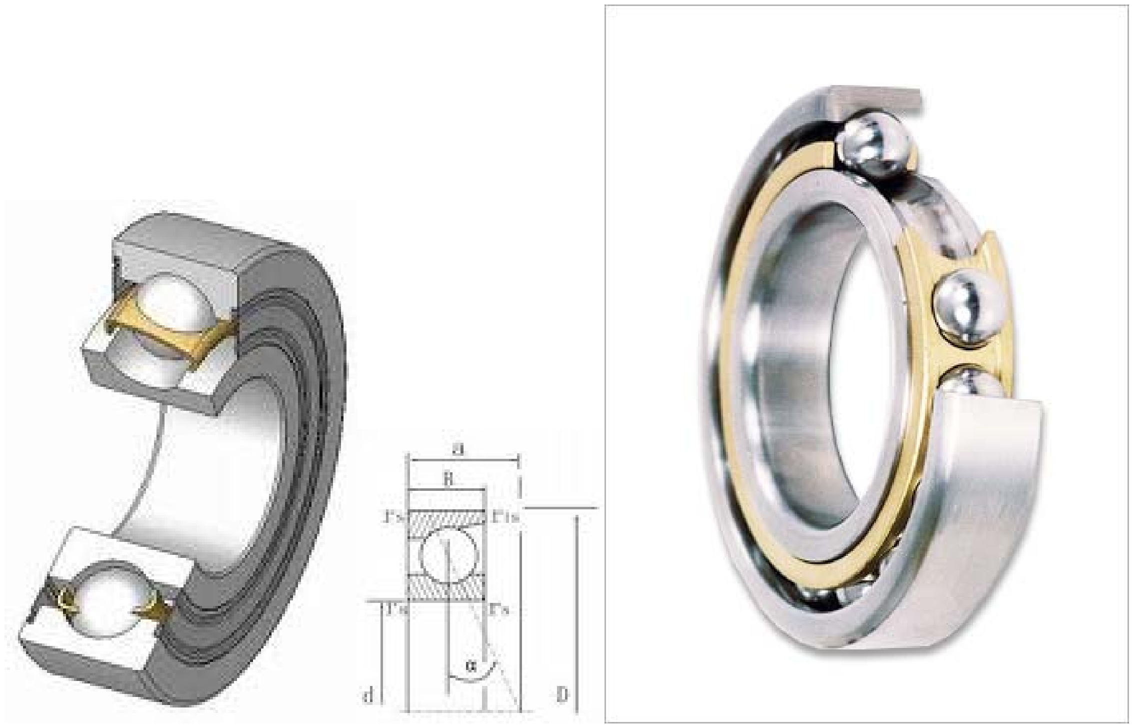


Figure 5-36 Angular contact ball bearings, capable of carrying a combination of axial and radial loading. Note how one side of the groove in both the inner and outer races provides more contact with the balls than the other side. The bearing must therefore be mounted in the correct orientation to carry the axial load.
http://www.google.com.au/search?client=safari&rls=en&q=angular+contact+ball+bearings+pictures

Figure 5-37 *Left:* A **BALL THRUST BEARING**; *Right:* A **ROLLER THRUST BEARING**. Both bearings are used in conjunction with **THRUST WASHERS**, one on top, one underneath, made from hardened and polished steel.
Courtesy The Timkin Company, at http://science.howstuffworks.com/bearing3.htm

2.3 Roller bearings

2.3.1 Cylindrical roller bearings

Whereas ball bearings have theoretical "point" contact between the balls and races, roller bearings have "line" contact and so can carry heavier loads. In practice, of course, both balls and rollers deform under load and contact between the rolling element and the races changes from a point or line to a small area.

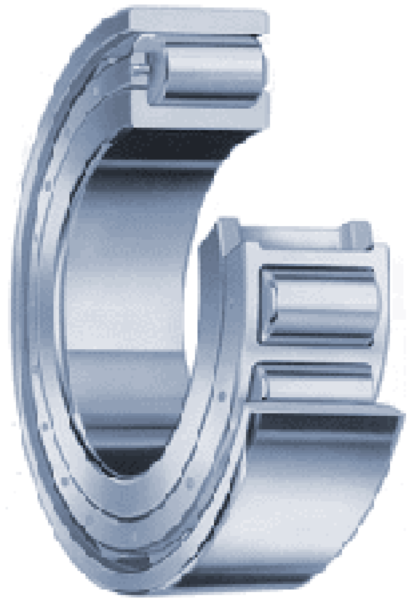


Figure 5-38 An example of a cylindrical roller bearing.
Courtesy The Timkin Company, at http://science.howstuffworks.com/bearing3.htm

In general, cylindrical roller bearings do not provide axial restraint – the rollers in their cage are free to slide axially along the outer race. Whilst this feature may be useful to allow for the change of shaft length due to heating, these bearings cannot be used unless there is provision elsewhere to provide axial location and, if necessary, carry axial loading or thrust.

Some types of cylindrical roller bearings do provide axial restraint in one direction by means of a shoulder in the outer race. Note that any axial or thrust loading carried by a roller bearing must be resisted by the ends of the rollers contacting the shoulders in the inner and outer races. Since this must result in sliding motion rather than rolling, axial loading must be kept low to avoid scoring, overheating and seizure.

2.3.2 Tapered roller bearings

Figure 5-39 *Left:* An example of a **TAPERED ROLLER BEARING.**
http://www.999autoworld.com/image_uploads/Tapered_Roller_Bearing.jpg
Right: A double row tapered roller bearing, used to increase the load-carrying capacity of the bearing and to provide axial restraint in two directions.
Courtesy The Timkin Company, at http://science.howstuffworks.com/bearing3.htm

Tapered roller bearings have very high radial-load capacity and high axial-load capacity in one direction. For this reason, tapered roller bearings are often used in pairs, mounted in opposite directions, to cater for high radial loads and axial loads in either direction. Tapered roller bearings are often used as in Fig. 5-40 in the wheel bearings of cars and heavy trucks. Note that each roller is actually a **FRUSTRUM** of a cone so that true rolling contact is maintained over the whole length of the roller. Also refer back to Figs 5-6 and 5-7 for examples of the use of angular contact and tapered roller bearings.

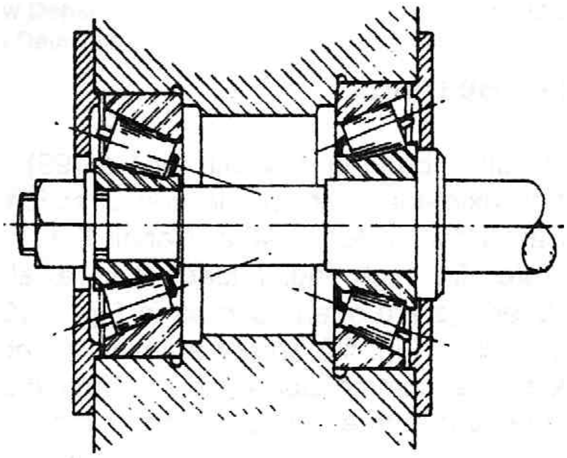


Figure 5-40 Schematic of an assembly of two tapered roller bearings mounted in opposite directions in order to locate a shaft which may be subjected to high radial forces and axial forces in either direction, e.g. mounting the front wheel of a car or truck onto its stub axle. Note the series of shoulders and tapers on the axle and the nut on the left-hand end which can be tightened just enough to take up all clearance and secure the hub assembly against looseness. In this simple diagram, there is no means of locking the nut to prevent loosening in service. A common method is to use a castle nut and split pin (Refer to detachable fasteners in Project 2). Nor is there any means of sealing lubricant into the housing.
Reproduced from J. Carvill, *The Student Engineer's Companion*, Butterworths, 1980, page 45.

2.3.3 Roller thrust bearings

Figure 5-41 **ROLLER THRUST BEARINGS** are again tapered rollers to maintain true rolling over the length of the roller. Roller thrust bearings have a greater load capacity than ball thrust bearings.

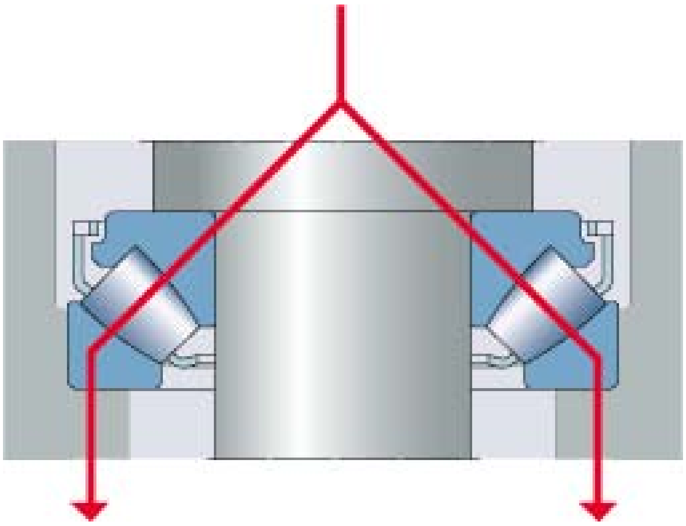


Figure 5-42 Tapered spherical rollers used as thrust bearings. The spherical feature allows self alignment to compensate for deflection under load.
Courtesy The Timkin Company, at http://science.howstuffworks.com/bearing3.htm

2.3.4 Needle roller bearings

Figure 5-43 Examples of needle roller bearings. One of the main advantages of needle roller bearings is their small diameter, so they can be fitted into small spaces. They usually do not have a separate inner race, running directly onto the shaft, which must be suitably hard and with a precision ground surface. When these bearings fail, they often damage the shaft surface and the shaft needs to be replaced. Compare with ball and roller bearings, which have an inner race so that bearing damage is normally confined to the bearing races and the shaft is undamaged.
http://www.nskamericas.com/cps/rde/xchg/na_en/hs.xsl/needle-roller-bearings.html

2.4 Bearing alignment

Ball and roller bearings are precision components and are manufactured with very small internal clearances. They therefore provide very accurate positioning of the shaft. However, due to the small clearances, they do not perform well if they are misaligned. If there are doubts concerning accurate alignment of the housing into which the bearing will fit (or the amount of deflection of the shaft on which they are mounted), **SELF-ALIGNING BEARINGS** may be specified, as shown in Fig 5-42. In these bearings, self-aligning is achieved by allowing the plane of the balls or rollers to tilt relative to the spherical race in the outer housing. Fig 5-44 shows a double-row ball bearing (which has greater radial load capacity than a single-row bearing) allowing the outer race to tilt within a spherical seating. An alternative construction (not shown) has an outer race with an external spherical surface, enclosed within an additional casing which has an internal spherical surface.

Figure 5-44 Double row spherical self aligning ball (top) and spherical roller (below) bearings to cope with angular misalignment.
http://www.nskamericas.com/cps/rde/xchg/na_en/hs.xsl/self-aligning-ball-bearings.html and
http://www.bearings-china.com.cn/Ball-Bearings/products_img/2008616181535.jpg

2.4.1 Pillow blocks

Figure 5-45 Example of a pillow block or plummer block.
http://www.nskamericas.com/cps/rde/xchg/na_en/hs.xsl/pillow-blocks-products.html

PILLOW BLOCKS, also known as **PLUMMER BLOCKS**, are a useful off-the-shelf component which can simplify shaft mounting in some cases. They are normally available with a range of different rolling contact bearings fitted within the housing – ball or roller, single or double row, **SELF ALIGNING** or **DEEP GROOVE** type, depending on the application and the probability of misalignment. The housing also makes provision for seals to retain lubricant, while the mounting feet make it easy to attach the housing to a base plate or frame.

2.4.2 Bearing preload

Since **all** engineering components deflect to some extent under load, shaft bearings which have been set up with zero clearance when there is no load on the shaft will almost certainly have some clearance or slackness when the shaft has a load applied. This is true whether the load on the shaft is radial, axial or a combination of the two. This clearance when running, which results in unnecessary wear of the bearings, can in many cases be overcome by **PRELOADING** the bearings.

Refer again to Fig. 5-40, reproduced below as Fig. 5-46. The outer races of the two tapered-roller bearings are located in the **BEARING HOUSING**. They cannot come closer together because each race is against a shoulder in the housing. The bearing inner races are mounted on the shaft. The right-hand inner race bears against a shoulder on the shaft. The left-hand inner race is held axially by the washer and nut on the end of the shaft. Tightening the nut will therefore push the two inner races closer together, squeezing them into the tapered outer races. Initial tightening of the nut will take up all the **CLEARANCE** in the bearing assembly. Further tightening of the nut will provide bearing **PRELOAD**. Preload may be regarded as negative clearance. Ideally, the preload should be sufficient to ensure that the bearings do not run slack (i.e. with clearance) under normal operating conditions, since clearance is known to increase the rate of wear of tapered roller bearings. However, too much preload may result in excessive loading and overheating of the bearing.

In practice, the adjusting nut in Fig. 5-46 will require some form of **LOCKING** to prevent it coming loose in service (refer to Project 2, Fasteners). The assemblies in Fig. 5-40 and 5-46 could achieve this by the use of a **SLOTTED NUT** and **SPLIT PIN** and this method is common practice in industry.

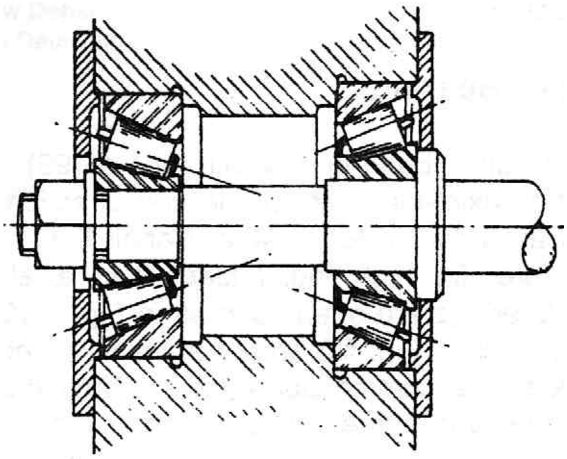


Figure 5-46 Repeat of Fig 5-40: An example of a shaft supported by a pair of tapered roller bearings. showing how bearing preload can be adjusted.
Reproduced from J. Carvill, *The Student Engineer's Companion*, Butterworths, 1980, page 45.

2.5 Lubrication of bearings

Lubrication of rolling contact bearings is important because it:

- Prevents corrosion.
- Greatly reduces the effects of the sliding friction present in all bearings, particularly roller bearings.
- Carries heat away from heavily loaded bearings.

Lubrication may be achieved by

- Drip, splash or mist (oil only).
- Lubricators (oil or grease, see Fig 5-28).

- Oil circulation within a gearbox by entrainment and splashing, etc.

Grease is a suitable lubricant provided rotational speed is not too high and mineral oils are good general purpose bearing lubricants, although many modern applications demand special high-pressure lubricants.

2.6 Sealing

Good sealing is essential. Seals should:

- Keep dirt out, thereby preventing premature wear of the bearing.
- Keep lubricant in, ensuring that the bearing (and possibly other components) will not run short of lubricant.

Refer to Part 3 of these notes for illustrations of shaft seals.

2.7 Characteristics of rolling contact bearings

- They have very low friction, particularly when starting.
- They require larger radial sizes than plain bearings but need shorter axial length.
- They are generally more costly than plain bearings.
- They have a finite life. The rolling elements and races eventually fail by flaking of the contact surfaces, a form of fatigue failure.
- Rolling contact bearings are not as quiet in operation as plain bearings. As progressive surface flaking occurs, the bearings become increasingly noisy in operation and provide ample warning of impending failure. Compare with plain bearings which can fail very rapidly and almost without warning.