Power Transmission

1. Bearings

A bearing is designed to:

• Reduce friction

• Support a load

• Guide moving parts – wheel, shafts, pivots

Reducing friction

Whether they are used in fleet, automotive or industrial applications, bearings perform the same function and have the same objective – to keep the shaft moving smoothly and consistently while reducing friction.

Supporting a load

A shaft will try to push the bearing in the same direction in which the load moves. The load is dependent on both weight and direction. If the wrong type of bearing is used it may not be able to carry the required load.

There are three types of loads (figure 36):

1. When the direction of the load (weight being moved) is at right angles to the shaft, it is called a "radial" load. The load pushes down on the bearing.

2. When the direction of the load is parallel to the shaft, it is called a "thrust" load. The load pushes sideways on the bearing.

3. When the direction of the load is a combination of radial and thrust, the load pushes down sideways on the bearing. This combination is called an "angular" load.

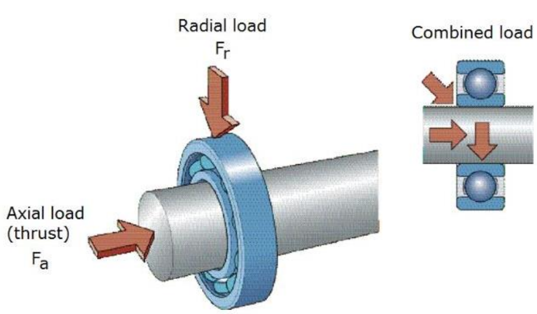


Figure 36. Loads on a Bearing

1.1. Rolling-Element Bearings

The rolling elements, shaped as balls or rollers, provide the cushion that eases the moving friction of the shaft within its housing. These elements keep the outer and inner races separated and enable them to move smoothly and freely. The shape of the rolling elements depends on the type of load, operating conditions, and particular applications. It is the rolling elements that distinguish the two basic bearing categories – ball bearings and roller bearings.

The parts of a bearing

A bearing's smooth performance is assured by a combination of four basic working parts (fig. 1):

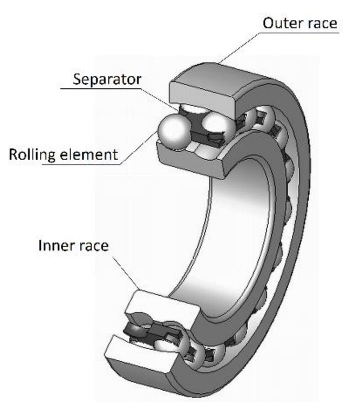
• Outer race (also called outer ring or cup)

• Inner race (also called inner ring or cone)

• Rolling elements (either balls or rollers)

• Separator (also called cage or retainer)

The outer race, or cup, is the bearing's exterior ring. Since it protects the bearing's internal parts, it must be machined smoothly and accurately. The inner race, or cone, is the part of the bearing that sits directly on the shaft.



One variation of roller bearings – the tapered roller – is used extensively for fleet, automotive and other vehicular applications. Its construction differs significantly from ball bearings and other types of roller bearings.

The rolling elements and both races slant inward, much like a cone. If you extend a line along the surface of the races and rollers, and also draw one through the bearing's axis, those lines would all meet at a common point (fig. 3). Those same lines along the surfaces of ball or cylindrical roller bearings are parallel. The advantage of this design is that the tapered rollers have a positive alignment with the shaft. That is, each roller will align itself perfectly on the tapered faces of the cup (outer race) and cone (inner race).

In addition to tapered roller bearings, there are a number of other roller bearing types including cylindrical and needle bearings.

1.2. Needle Roller Bearings

The needle roller bearing is a variation of the cylindrical roller bearing. The main difference is in roller design capacity. The rollers are thinner in diameter, but there are more rollers per bearing. Full complement needle roller bearings do not have a cage. In this type of bearing one roller pushes against the other, holding everything in place.

Applications

- Transmissions
- Alternators
- Steering gears
- Universal joints

Installation

Cleanliness, proper tools, and specific mounting guidelines are needed to assure proper installation as well as long-lasting bearing performance. Improper bearing installation is a common cause of premature bearing failure.

A bearing cannot operate properly if the shaft or housing is not in good condition. Before mounting the bearing, be sure shaft and housing bore dimensions are within recommended tolerances. The bearing seat in the housing bore should be perfectly round and not tapered. The shaft and housing should also be clean and free from nicks and burrs. Extra care should be taken when mounting a bearing in a solid housing. Before any installation pressure is applied, the outer race should be perfectly square with the housing bore.

Operating temperature

Type of load, shaft speed, and amount of friction all contribute to one of the most critical conditions for operation – temperature. Each component of the bearing must be constructed of materials that not only handle the load, but also accommodate temperature fluctuations.

Not all heat is due to environment. The bearings themselves may cause excessive heat due to:

1. A too heavy load, resulting in deformed races and rollers

2. Friction between the rolling elements, retainer and races

3. Excessive churning from too much lubricant

4. Surface friction from too little lubricant

Lubrication

Using the right type and amount of lubricant for the job is another factor critical to bearing performance. Whenever bearing use causes excess friction, heat rises accordingly. Regular lubrication helps relieve the heat that results from bearing friction.

2. Gears

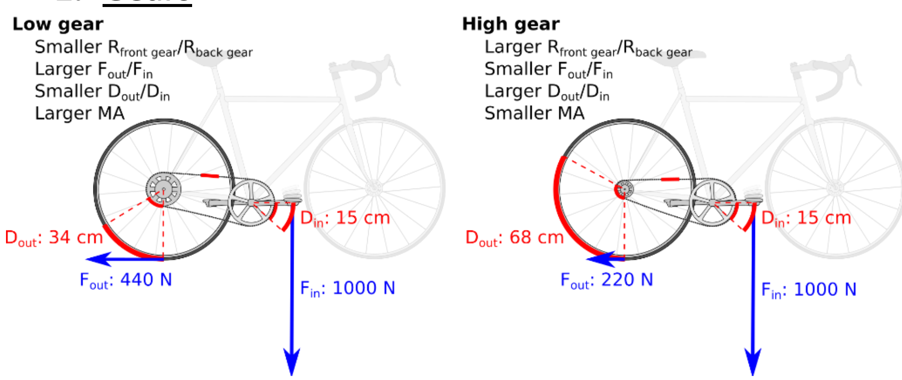


Figure 37. Gear Ratios

Important definitions

1. Velocity ratio=m_V=angular velocity of output gear/angular velocity of input gear=pitch diameter of input gear/pitch diameter of output gear

2. Torque (Force) ratio=m_T=torque at output gear/torque at input gear

3. $m_T=1/m_V$

4. Gear ratio=$m_G=N_{gear}/N_{pinion}$, m_G is almost always greater than one

Fundamental law of tooth gearing

Velocity ratio must be constant as gears rotate: Angular velocity ratio=ratio of distances of P from centers of rotation of input and output gear.

Fundamental law of gearing

The common normal of the tooth profiles at all points within the mesh must always pass through a fixed point on the line of the centers. This point is called the *pitch point*. When this occurs, the gear set's velocity ratio will be constant through the mesh and equal to the gear ratio.

3. Belt Drives

Belts and *cables* are very common power transmission elements because their elastic nature enables them to pass over round objects (pulleys) typically with a high degree of efficiency. The term *power transmission* literally means that the power output from the device equals the product of the efficiency and the power input to the device. Therefore, analyzing any power transmission system really is as simple as keeping track of the products of speeds and torques (or forces) and the efficiencies.

Rotary power is created by electric motors, combustion engines, wind mills, etc. Motors generally operate too fast and deliver too low a torque to be appropriate for the final drive application. The torque is increased in proportion to the amount that rotational speed is reduced. The high speed of the motor makes belt drives good for the first stage of reduction.

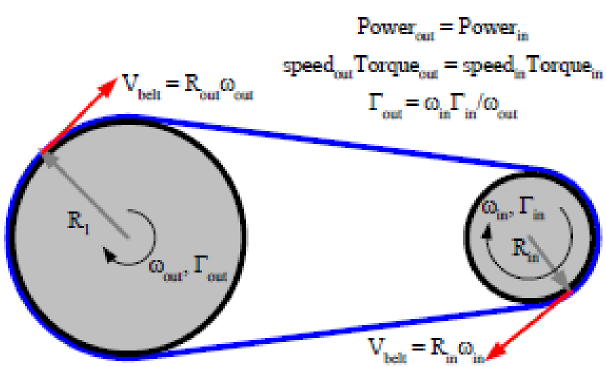


Figure 38. Belt Drive Ratios

Key Belt Drive Design Characteristics

1. Environment

2. Load cycles

3. Service life

4. Belt characteristics

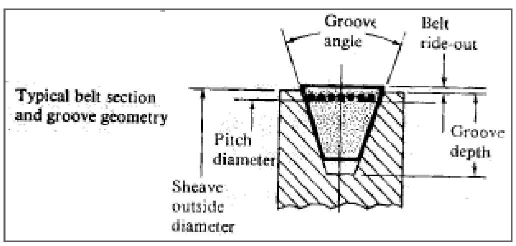
5. Sheave diameter and Center distance

6. Power requirements

3.1. V-Belt Drive

A belt is a flexible power transmission element that fits securely on a set of pulleys or sheaves. When the belt is used for speed reduction, the smaller sheave is mounted on the high speed shaft, like the shaft of an electric motor. The larger sheave is then put on the driven machine.

A common type of belt is the V-belt drive. The V-shape causes the belt to wedge tightly into the groove, increasing friction and allowing high torques to be transmitted before slipping occurs. Most belts have high-strength cords positioned at the pitch diameter of the belt cross section to increase the tensile strength of the belt.



4. Chains

Chains are often used to transmit very large forces and torques relative to their size. There are many different types of chains, and one of the most common types is the *roller chain* which uses metal *links* connected together by *pins* and spaced apart by *bushings*. *Sprockets*, toothed wheels which are a special form of gear, positively mechanically engage the chain so there can be no slip. Accordingly, chains are extremely versatile. They can be used to transmit power between two rotating shafts, and they can also be used to convert rotary to linear motion or to enable linear to linear motion.

The most common type of chain is the roller chain, in which the roller on each pin provides exceptionally low friction between the chain and the sprockets. The roller chain is classified by its pitch, the distance between corresponding parts of adjacent links. The pitch is usually illustrated as the distance between the centers of adjacent pins. A standard roller chain carries a size designation from 40 to 240.

Chains are a very robust means to transmit very large forces and torques.

Given an applied chain tension *T*, be it from a linear or rotary motion application, an equivalent tension has to be determined to reflect the type of load and number of strands of chain required. An equivalent tension must be below the acceptable limits for the particular chain used, as specified by the manufacturer, in order to obtain the desired life:

$$_{\text{equivalent applied}}T = T \times K_{\text{service factor}} \times K_{\text{strand factor}}$$

• The total length of chain loop should not exceed 100 pitches

• Number of sprocket teeth: <17 low speed, 17-21 moderate speed, >21 high speed

• Due to the manner in which the rollers engage the sprocket teeth, assuming the driver sprocket is rotating at a constant speed, the driven sprocket speed will vary by cos(2π/Nteeth on the driven sprocket)

• Number teeth large sprocket/Number teeth small sprocket < 7

• Noise increases with increasing Load/Maximum Load

• At least 1/3rd of the teeth on a sprocket should engage the chain

• Idler sprockets can be used to maintain tension

• Lubricated chain and sprocket life can be long because the teeth have nominal rolling contact with the bushings, although there is enough slip to require lubrication

• Use protective covers to keep stuff out of the chain drive!

ANSI Steel Roller Chain (units of inches and pounds)							
Chain #	Pitch	Roller		Pin Diam.	Link plate thickness	Breaking Load	Working Load
		Diam.	Width				
25	1/4	0.130	0.125	0.091	0.030	1050	140
35	3/8	0.200	0.188	0.141	0.050	2400	480
41	1/2	0.306	0.250	0.141	0.050	2600	500
40	1/2	0.313	0.313	0.156	0.060	4300	810
50	5/8	0.400	0.375	0.200	0.080	7200	1400
60	3/4	0.469	0.500	0.234	0.094	10000	1950
80	1	0.625	0.625	0.312	0.125	17700	3300

5. Clutches, Cam and Couplings

5.1. Clutches

Clutches and differentials are very important transmission components whose operation is normally transparent to the user until they are needed. A clutch normally behaves as a rigid element until a certain torque is exceeded, and then it slips. A standard or “open” differential equalizes the torque on two output shafts while constraining the sum of their rotary displacements to be equal to the input rotary displacement. In the case of an automotive clutch, the clutch allows slip between the engine and the transmission so the engine will not stall at low speeds. In the case of a robot or manufacturing equipment, a clutch is typically used to prevent overloading of components. For example, a clutch can prevent gear teeth from being sheared off when a driven member encounters a rigid object. Clutches can also be configured to resist torque in only one direction. A simple form of this type of clutch can be made by pressing a spring over the ends of two shafts, and anchoring it only to the driving shaft. The most common form of clutch is a simple mechanical clutch where one plate is forced against a second plate through the use of a spring. By adjusting a screw to change the pressure on the spring, the slip torque can be adjusted. The design parameters affecting a clutch’s torque capacity are: the diameter of the plates, the coefficient of friction, and the force between the plates.

Clutches and differentials allow for differential velocities between rotating shafts. A classic example is when a car makes a turn, all the wheels have the same instant center, but the radius from each wheel to the instant center is different. Thus, each wheel travels a different distance along an arc at the same time, and a *differential* is needed to enable the speed difference to occur. However, if one wheel is on ice, and another wheel is on dry pavement, the wheel on ice will spin. Limited slip differentials typically use spring-loaded clutch plates to ensure some torque is always transmitted to both wheels. Other designs use a centrifugal force to engage locking features. New designs use electromagnetic clutches to optimize torque transfer to the wheels. Clutches can be activated mechanically or electrically to control the torque transmitted between shafts, while allowing differential velocity to occur.

5.2. Couplings

Couplings are required between rotary and linear actuators and driven components because the actuators are intended to move in one degree of freedom (linear or rotary), but they can never be perfectly aligned. As a component moves, it will not always be aligned with the actuator. The product of the net difference in motion with the stiffness of the connection between the two systems yields the misalignment force on the actuator. If a rigid coupling is used the forces can be extremely high, and something, usually the bearings, will have to give and they will soon fail. Furthermore, a significant portion of the system’s power can be expended in the process. When a coupling is ideal, and only restrains the intended motion with negligible effect (stiffness) in all other axes, it is said to be a *non-influencing coupling*.

There are three strategies for coupling designs. The first is to leave clearance between geometric features so the motion occurs across a sliding bearing interface without causing large bearing loads. A linear example is a clevis at the end of a hydraulic cylinder, where there is clearance between the clevis pin and the bore into which it fits. A rotary example is an *Oldham* coupling which is comprised of two cylinders, each with a slot cut in their faces, and each attached to the ends of two shafts that are facing each other. A plastic disk with raised rectangular features on each side is placed between the cylinders. Small motions between the shafts are accommodated by the plastic keys in the slots. When more torque and misalignment capacity are needed with a more linear response, four jaws on each cylinder face each other and then an eight-armed plastic *spider* insert acts as the interface between the two.

The second strategy is to use a connection that is only stiff in the desired direction. An example is a tube with circumferential slits cut in it (a *helical* coupling). Merely using a piece of plastic tubing is not acceptable because if it is short enough to provide enough torsional rigidity, it is often not sufficiently radially compliant. Super precision instruments may go to extreme measures and use *taut wire couplings*. The third strategy is to use linkage elements (linear and or revolute joints) to create a mechanism that transmits the appropriate force or torque. A common example of this type of strategy is to use universal (*Hooke's*) joints at the ends of a drive shaft. Precision instruments often transmit forces using *wobble pins*, which are pins with conical ends that rest in a spherical cup.

Figure 38. Couplings

5.3. Cams

A *cam* is a machine element whose specially shaped *lobes* are followed by a *cam follower,* which causes the cam profile to be imparted on another object. A common application is in an internal combustion engine where the cam is driven by a chain or belt connected to the *crankshaft*. The *cam lobes* are thus synchronized with the crankshaft rotation to open and close intake and exhaust valves as required. The shape of the cam *lobe* determines not only when a valve is opened, but how fast, and how long it stays open, which is called the *dwell time*. In a modern overhead cam engine, the *cam* pushes on a *cam follower,* which pushes on the *valve stem*. The *valve* is held in a normally closed position by *valve springs,* which, through the chain of elements, cause the cam follower to remain in contact with the cam and keep the valve normally closed.

A *cam* is a rotating shape whose angular motion is converted into output motion by a *cam follower* which rides on the cam surface. A *cam profile* can be designed to create corresponding *acceleration*, *velocity*, *position*, and *dwell* profiles in a mechanism (e.g., an engine valve).

Cams may include sliding or rolling elements, each with their respective advantages and disadvantages:

- Rolling elements provide the highest degree of efficiency, but they take up more space
- Sliding elements are very compact, and can be efficient if the speed is high enough to maintain oil film lubrication

<u>Camshaft</u>

The camshaft controls the opening and closing of the valves. There is one lobe on the camshaft for each valve in the engine. Camshaft lobe design dictates three things:

• How far the valve opens

• How fast the valve opens

• How long the valve opens

Depending on the engine type, the camshaft can be located either in the engine block or over the head (OHC) or double OHC (DOHC).

6. <u>Oil and Lubrication Systems</u>

6.1. Functions of Lubrication

One function of a lubrication system is to reduce friction. Friction occurs between all surfaces in contact. When moving surfaces come together, friction tends to slow them down.

Lubrication reduces wear on moving parts. Clearances fill with oil so that engine parts move or float on layers of oil instead of directly on each other. Much less power is needed to move them, and that’s a plus. Lubrication helps cool an engine. It collects heat from the engine and then returns to the sump, where it cools. It helps absorb shock loads. A power stroke can suddenly put as much as 2 tons of force on main bearings. Layers of oil cushion this loading. Oil is also a cleaning agent. It collects particles of metal and carbon and carries them back to the sump. Larger pieces fall to the bottom.

Grease, specifically, has some additional special functions:

1. Reduces maintenance time. There are no minimum grease levels to maintain, so lubrication cycles are less frequent.

2. Is confined to the housing or bearing. This means a simpler seal design can be used to retain lubricant and exclude dirt.

3. Grease is more viscous than oil lubricants.

6.3. Oil Additives

Special chemicals called additives are added to the base oil by oil companies. Different combinations of these additives allow the oil to do different jobs.

a. Extreme-pressure additives coat parts with a protective layer so the oil resists being forced out under heavy load.

b. Oxidation-inhibitors stop very hot oil from combining with oxygen in the air to produce a sticky material, like tar, which clogs galleries.

c. Corrosion-inhibitors help stop acids from forming that cause corrosion, especially of bearing surfaces.

d. Anti-foaming agents reduce the effect of oil churning in the crankcase and minimize foaming.

e. Detergents reduce carbon deposits on parts like piston rings and valves.

f. Dispersants collect particles that can block the system, separate them from each other, and keep them moving. Then they will be removed when the oil is changed.

6.4. Lubricant selection

Lubricant selection depends on a combination of factors: the type of housing, operating temperature, operating speed and any particular requirement of that bearing type. In all cases, the best guide for proper selection of a lubricant is the recommendation of the vehicle's manufacturer.

There are two lubricant types – grease and oil. Due to the design of equipment and the conditions under which it must operate, grease is the more widely used lubricant. Various types of grease are available and should be selected carefully. There are certain guidelines to follow when selecting the right lube for the job. For example, open bearings are only lubricated with a film of oil or light grease to protect them from corrosion before use. They must also be lubricated while running. Sealed and shielded bearings are grease packed from the factory and are sealed for life. The lubrication used in ball and other bearing types is usually a sodium or lithium based grease or oil.

As a general rule, bearings run the coolest, and with the least amount of friction, when the bearing surfaces are kept apart with a minimal amount of light-bodied lubricant.

Use a heavier lubricant only if:

• Operating conditions require it

• The load is too heavy for the lube

• It is specifically called for in the application

Note that heavy penetration grease will normally increase friction.